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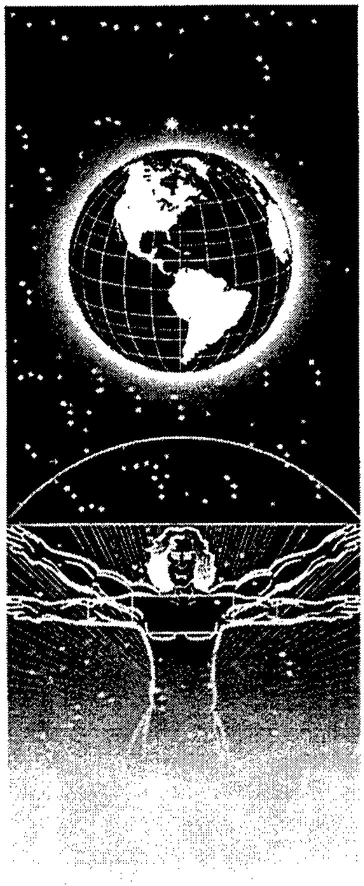

UNITED STATES AIR FORCE RESEARCH LABORATORY

Background Definitions and Metrics for Sound Properties in Air and in Water Relevant to Noise Effects

Raymond C. Cavanagh
Hyrum Laney

SCIENCE APPLICATIONS INTERNATIONAL CORP.
1710 Goodridge Drive
McLean VA 22102

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Human Effectiveness Directorate
Crew System Interface Division
2610 Seventh Street
Wright-Patterson AFB OH 45433-7901

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FOR THE COMMANDER

John M Reising

JOHN M. REISING
Crew System Interface Division
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This is one of five companion reports, each of which deals with one aspect of the problem of assessing the effects of noise from military aircraft on marine life: metrics for sound properties in air compared to sound properties in water; criteria and thresholds for injury and harassment of protected marine life; animal population statistics; and risks of impact from subsonic/supersonic aircraft noise. The purpose of the effort is to establish technically sound estimation procedures for determining the effects of military aircraft noise on marine life, without which the Air Force risks inadvertent violations of the law and becomes vulnerable to litigation and interference with military operations. Objectives include developing procedures for predicting properties of sound waves in air and under water as generated by both subsonic and supersonic aircraft flights; estimating the effects of sound on marine life, both in air and under water; and determining populations of marine life at risk, as functions of aircraft, flight path, and time of year. This volume specifically focuses on the first topic in the list: definitions and metrics.

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EXECUTIVE SUMMARY

This is one of five companion reports prepared under the sponsorship of Code HECB of the Air Force Research Laboratory (originally funded by Code AL/OEBN, Armstrong Laboratory of Wright-Patterson Air Force Base). Each of the reports deals with one aspect of the problem of assessing the effects of noise from military aircraft on marine life: (1) metrics for sound properties in air compared to sound properties in water, (2) criteria and thresholds for injury and harassment of protected marine life, (3) animal population statistics, and (4)/(5) risks of impact from subsonic/supersonic aircraft noise.

The end purpose of this multi-year contract effort is to establish technically sound estimation procedures for determining the effects of military aircraft noise on marine life. Without such procedures, the Air Force risks inadvertent violations of the law and becomes vulnerable to litigation and interference with military operations.

Objectives of the contract effort include developing procedures for:

1) Predicting properties of sound waves in air and under water as generated by both subsonic and supersonic aircraft flights
2) Estimating the effects of sound on marine life, both in air and under water
3) Determining populations of marine life at risk, as functions of aircraft, flight path, and time of year.

This volume specifically focuses on the first topic in the list: definitions and metrics.

The quantities and units used for acoustics in the atmosphere are complicated and often confusing, with "traditional" metrics and units often quite different from standard and modern ones. The same is true for the quantities and units of underwater sound. When dealing with both, as in the penetration of sound waves into water or the comparative effects of noise on animals in both media, the physical quantities and their metrics can be complicated if not confusing.

This paper is a collection of equations, formulas, and notes, with references when appropriate, gathered during research on the problem of the effects of noise on marine life. For that reason, it covers the metrics and units often encountered, as well as conversion factors and relationships. We have also included an Appendix on the SI system of units and one on conversion of units.

The motivation for gathering this information was our concern over the misunderstandings and inaccuracies evident in a variety of written statements in the press and the technical literature.

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1.0 INTRODUCTION

This is one of five companion reports prepared under the sponsorship of Code HECB of the Air Force Research Laboratory (originally funded by Code AL/OEBN, Armstrong Laboratory of Wright-Patterson Air Force Base). Each of the reports deals with one aspect of the problem of assessing the effects of noise from military aircraft on marine life: (1) metrics for sound properties in air compared to sound properties in water, (2) criteria and thresholds for injury and harassment of protected marine life, (3) animal population statistics, and (4)/(5) risks of impact from subsonic/supersonic aircraft noise.

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The motivation for gathering this information was our concern over the misunderstandings and outright errors evident in a variety of written statements in the press and the technical literature.

Chapter 2 provides fundamental definitions from acoustics and fluid dynamics relevant to noise effects. With few exceptions, the material addresses topics found to be points of ambiguity or confusion in the literature and noise impact studies. Special attention is given to parameters used as metrics for noise effects (e.g., positive impulse, intensity level).

Chapter 3 continues with definitions of terms used in assessing noise impacts and effects. These include signal types, detection terms, hearing threshold shifts, SEL, etc.

Chapter 4 was added to address the distinctions of acoustic properties and propagation for the multiple types of media encountered in the risk assessment process. Propagation of sound in air is different from that in water for many reasons. A good example is flow, present in the form of winds and turbulence in air, but of little importance in water (since currents move slowly relative to the sound speed). The best way to check on the applicability of an estimate of sound properties is to examine the basic assumptions and 'wave equation' for that case. Accordingly, some of the more commonly used sets of assumptions and equations are presented.

Besides a reference list in Chapter 5, there are several appendices which were designed to help with units and conversions associated with sound in air and in water. Included are intensity, energy flux density, air/water relationships, and decibel conversions.

The authors are pleased to acknowledge the guidance and interest of the sponsor over the course of the contract, especially Major Jeffrey Fordon, Dr. Robert Lee, and Captain Michael Carter.

2.0 DEFINITIONS AND NOTES ON TOPICS OF FLUID DYNAMICS AND ACOUSTICS

Because of the complexities in compliance regulations and documentation dealing with sound, it is important to have ready access to definitions of fundamental quantities, such as pressure, intensity, particle velocity, etc. The following definitions and notes are largely derived from standard reference materials.

2.1 Elasticity

Elastic (Mechanics): Capable of sustaining deformation without permanent loss of size or shape. (MHDPM, 1978)

Elastic Wave (Physics): A wave propagated by a medium having inertia and elasticity, in which displaced particles transfer momentum to adjoining particles and are themselves restored to their original position. (MHDPM)

Bulk Modulus Of Elasticity (Mechanics): The ratio of the compressive or tensile force applied to a substance per unit surface area to the change in volume of the substance per unit volume. Also known as *bulk modulus, compression modulus, modulus of volume elasticity, modulus of compression, hydrostatic modulus.* (MHDPM)

Strain (Mechanics): Change in length of an object in some direction per unit undistorted length in some direction, not necessarily the same. (MHDPM)

Stress (Mechanics): The force acting across a unit area in a solid material in resisting the separation, compacting, or sliding that tends to be introduced by external forces. (MHDPM)

2.2 Viscosity

Viscosity (Fluid Mechanics): Energy dissipation and generation of stresses in a fluid by the distortion of fluid elements. Also known as *flow resistance, internal friction.* (MHDPM, 1978)

Viscous Fluid (Fluid Mechanics): A fluid whose viscosity is sufficiently large to make the viscous forces a significant part of the total force field in the fluid. (MHDPM)

2.3 Compressibility and Compressional Waves

Compressible Fluid: Fluid has property that applied force or pressure results in increased density.

Compressible Flow (Fluid Mechanics): Flow in which the fluid density varies. (MHDPM)

Compressible-Flow Principle (Fluid Mechanics): The principle that when flow is large, it is necessary to consider that the fluid is compressible rather than to assume that it has a constant density. (MHDPM)

Wave (Physics): A disturbance which propagates from one point in a medium to other points without giving the medium as a whole any permanent displacement.

P Wave or Primary Wave or Compressional Wave (Physics): A disturbance traveling in an elastic medium; characterized by changes in volume and by particle motion parallel with the direction of wave movement. Also know as *dilatational wave*; *irrotational wave*; *pressure wave.* (MHDPM)

2.4 Shear Waves

Shear Wave (Mechanics): A wave that causes an element of an elastic medium to change its shape without changing its volume. Also known as *rotational wave.* (MHDPM, 1978)

S Wave or Secondary Wave or Shear Wave (Geophysics): A seismic body wave propagated in the crust or mantle of the earth by a shearing motion of material. Also known as *distortional wave*; *secondary wave*; *shake wave*; *tangential wave*; and *transverse wave.* (MHDPM)

Note: Static *fluids* are generally unable to support shear stresses.

2.5 Sound

Sound: Paraphrasing Beranek (1986), define *sound* as a disturbance propagated through an elastic medium which causes a change in pressure or a displacement of particles.

Sound: Newton's Principia of 1686 described *sound* as pressure pulses transmitted through neighboring fluid particles (Pierce, 1989).

Sound: As Pierce (1989) points out, "...the term *'sound'* implies not only the phenomena in air responsible for the sensation of hearing, but also whatever else is governed by analogous physical principles." Hence, *ultra-* and *infra-sound*, *underwater sound*, *sound in solids*, and *structure-borne sound* are included. *Sound* is strictly mechanical wave motion.

2.6 Acoustics

Acoustics: "Acoustics" is the science of *sound*, including its production, transmission, and effects. "*Sound*" here has the broad interpretation given above. [ANSI S1.1960 (R1976)]

Acoustic Wave (Acoustics): An elastic non-electromagnetic wave that has frequency which may extend into the giga-hertz range; one type is a surface acoustic wave, and the other is a bulk or volume acoustic wave. (MHDPM)

Acoustic Phenomena: *Acoustic* disturbances are usually regarded as small-amplitude perturbations to an ambient state. For a fluid, the ambient state defines the medium through which the disturbance propagates and is characterized by pressure, density and fluid velocity when the perturbation is absent (after Pierce, 1989). In this context, the total pressure is the sum of the ambient pressure and the acoustic pressure. Likewise for the density.

Non-linear Acoustics: When the perturbations to the ambient state have finite amplitude, the "acoustics' approximations to the fundamental equations do not apply. Since the equations are no longer linear, the finite-amplitude processes are called *non-linear acoustic* processes. Examples are sonic booms, underwater explosive shock waves, and parametric sources (e.g., Beyer, 1974, and Chapter 4). Non-linear acoustics is considered a branch of acoustics.

2.7 Density

Density: For a static, homogeneous volume of matter, *density* is the mass per unit volume. In sea water, the average *density* is about 1026 kg/m^3, or 1.026 g/cm^3. In air, *density* varies substantially with altitude and with time. A typical value at sea level and 20 degrees C. is 1.225 kg/m^3 or 0.001225 g/cm^3. (e.g., List, 1984)

2.8 Pressure

Pressure (Mechanics): A type of stress which is exerted uniformly in all directions; its measure is the force exerted per unit area. (MHDPM)

In a fluid (gas or liquid), pressure at a point is defined as follows. For an arbitrarily small area containing the point, the *pressure* is the normal force applied to the small area divided by the size of the small area.

Note: For a fluid at rest and under *pressure*, the force against any area within or bounding the fluid is normal to the area. Because *pressure* is a force applied to a unit area, it does not necessarily generate energy. *Pressure* is a form of stress, and as such has no direction assigned to it. It is a scalar quantity.

Pressure has units of force/area. The SI derived unit of pressure is the pascal (Pa) defined as one N/m^2. Alternative units are many (lbs/ft^2, lbs/in^2, bars, inches of mercury, etc.); some are listed at the end of this report.

2.9 Static Pressure

Static Pressure (Acoustics): At a point in a fluid (gas or liquid), the *static pressure* is the pressure that would exist if there were no sound waves present (paraphrase from Beranek, 1986). For a fluid at rest and under pressure, the force against any area within or bounding the fluid is normal to the area.

Static Pressure Equations
The relationship between the static pressure p(z) and its height z from the lower boundary of a fluid at rest is given by

$$dp/dz = -\rho g$$

where $\rho(z)$ is the fluid density and g is the acceleration of gravity. Hence,

$$p(z) = \int -\rho g dz = -g\int \rho dz$$

Static Pressure in Sea Water (Hydrostatic Pressure)

In the ocean, let z = 0 be the surface and z a point below the surface (z>0). Then

$$p(z) = p(0) + \rho gz = 1 \text{ atmosphere} + (10^7 \text{ kg/m}^3)(10\text{m/s}^2)(z)$$

$$= 1 \text{ atm} + 1 \text{ atm } (z/10)$$

for z in meters and p in atmospheres. This is the familiar rule that pressure in the ocean increases by one atmosphere every 10 m of depth. One atmosphere is about 10^5 Pa, 1 bar, 14.5 lb/in^2, etc. In the atmosphere and under water, the static pressure is the result of gravity acting on the mass of the medium. Because forces are balanced, no net energy results under static conditions.

2.10 Acoustic Pressure

Without limiting the discussion to small amplitude or linear waves, we can define *acoustic pressure* as the residual pressure over the "average" static pressure caused by a disturbance. As such, the "average" *acoustic pressure* is zero. Here the "average" is usually taken over time. *Peak Pressure* almost always refers to the absolute maximum pressure observed at a point in space over time.

Mean-Square Pressure is usually defined as the short-term time average of the squared pressure:

$$\frac{1}{\tau}\int_{T}^{T+\tau} p^2(t)dt,$$

where τ is on the order of several periods of the lowest frequency component of the time series.

RMS Pressure is then the square root of the mean-square pressure.

2.11 Impedance

Specific Acoustic Impedance (Z_s) is the complex ratio of the effective sound pressure at a point of an acoustic medium or mechanical device to the effective particle velocity at that point. The SI-derived units are N•s/m3 = Pa•s/m, called an 'acoustic rayl' or 'rayleigh.' (after Beranek, 1986)

Specific Acoustic Resistance and Reactance are, respectively, the real and imaginary parts of Z_s, the specific acoustic impedance.

Characteristic Impedance: The characteristic impedance of a surface has the same definition as the specific acoustic impedance except that the pressure wave is assumed to be planar. In that case, the average pressure and average particle velocity have ratio ρc, where ρ is the fluid density and c the sound speed.

2.12 Energy Density

For fluid ambient density ρ_0, acoustic wave pressure p, local sound speed c, and particle speed in direction of propagation u, the acoustic *kinetic-energy density* is $\frac{1}{2}\rho_0 u^2$ and the *acoustic potential-energy density* is $\frac{1}{2} p^2/\rho_0 c^2$. Units are those of energy per unit volume (J/m^3 in SI units). For plane waves, $p = \rho_0 c u$, so that

$$\tfrac{1}{2} p^2/\rho_0 c^2 = \tfrac{1}{2} \rho_0 u^2,$$

and the two components are equal. *Total energy* is then $p^2/\rho_0 c^2 = \rho_0 u^2$.

2.13 Acoustic Intensity (Acoustic Power Density)

Acoustic intensity is energy transported per unit area and time in the direction of propagation. Alternate measures include energy flux (Pierce, 1989) and power density. In the general case, *intensity* is the *vector* quantity:

$$\mathbf{I} = p\mathbf{u},$$

where **u** is particle velocity (e.g., Crocker and Jacobsen, 1997, or Fahy, 1995)

Under conditions consistent with the acoustic wave equation, the *intensity* (I) can be found from:

$$I = pu$$

where p is pressure and u is the component of the particle velocity in the direction of propagation (Beranek (1986) states this explicitly via $u = |\mathbf{u}|\cos\varphi$.). Units are those of power per unit area (or pressure times velocity), with SI-derived values: $Pa{\cdot}m/s = W/m^2$.

In the case of plane waves, $p = (\rho c)u$ (see 2.11). Hence, the *intensity* is the familiar:

$$I = p^2/\rho c$$

SI-derived units include:

$$W/m^2 = Pa^2/(Pa{\cdot}s/m) = Pa{\cdot}m/s$$

Some acousticians call I (as defined above) the *instantaneous intensity*.

2.14 Equivalent Plane Wave Intensity

As noted by Bartberger (1965) and others, it is general practice to measure (and model) pressure (p) or rms pressure (p_{rms}), and then infer an intensity from the formula for plane waves in the direction of propagation:

$$\text{Intensity} = (p_{rms})^2/\rho c.$$

Such an inferred intensity should properly be labeled as the *equivalent plane-wave intensity* in the *propagation direction.*

2.15 Spectra

Autocorrelation Function

For a stationary random process x(t), the *autocorrelation function* is

$$R(\tau) \equiv E\{x(t+\tau)x^*(t)\},$$

where E denotes expected value and x* the conjugate of x. For deterministic time series x(t),

$$R(\tau) \equiv \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t+\tau) \bullet x^*(t)dt$$

Power Spectrum (Power Spectral Density)

The *power spectrum* of x(t) is defined as the fourier transform of R(t):

$$S(\omega) = \int_{-\infty}^{\infty} e^{i\omega t} R(t)dt,$$

when the integral exists. In that case,

$$R(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega)e^{-i\omega t} d\omega.$$

Hence, R and S are transform pairs.

As an alternative definition, the power spectrum S(ω) of x(t) is given by

$$S(\omega) \equiv \lim_{T\to\infty} E\left\{ \frac{1}{2T} \left| \int_{-T}^{T} x(t)e^{i\omega t} dt \right|^2 \right\},$$

provided that $\int_{-\infty}^{\infty} |t\,R(t)|dt < \infty$ and E again means expected value.

Power Spectrum for Pressure Signal

If the time series for x(t) is pressure p(t), then the *power spectrum* is

$$S(\omega) = \lim_{T \to \infty} E\left\{ \frac{1}{2T} \left| \int_{-T}^{T} p(t) e^{i\omega t} dt \right|^2 \right\}.$$

It has units of squared pressure per unit frequency, or Pa^2/Hz for SI.

Spectrum Level at frequency f is the total sound pressure level in a 1-Hz band about f. It is meaningful only for sounds having a continuous spectrum (i.e., signals with some sound in all neighboring frequency bands) (after Urick, 1983)

Band Level refers to the level in a frequency band greater than 1 Hz. (Urick, 1983)

2.16 Wave Equations, Particle Velocity

Wave Equation (Physics): (1) In classical physics, a special equation governing waves that suffer no dissipative attenuation; it states that the second partial derivative with respect to time of the function characterizing the wave is equal to the square of the wave velocity times the Laplacian of this function. Also known as classical wave equation and d'Alembert's wave equation. (2) Any of several equations which relate the spatial and temporal dependence of a function characterizing some physical entity which can propagate as a wave, including quantum-wave equations for particles. (MHDPM)

Particle Velocity (Acoustics): The instantaneous velocity of a given infinitesimal part of a medium, with reference to the medium as a whole, due to the passage of a sound wave. (MHDPM)

Note: For a plane propagating wave, the *particle velocity* has the same direction vector as the normal to the wave front. In that case, the particle velocity is equal to the pressure normalized by the impedance.

Governing Equations: More rigorous definitions of acoustic quantities without some form of circular reasoning require consideration of the equations which define them. From Pierce (1989), the equations governing the fluid's ambient state and the "acoustic" disturbance in the fluid are derived from the usual conservation of mass, motion of a fluid, and pressure-density equations. See Section 4 for a review of some of the more important formulations.

2.17 Definitions Related To Sound Sources – Projectors

Source Intensity and Source Level

Define *source intensity*, $I(\theta,\phi)$, as the intensity of the projected signal referred to a point at unit distance from the source in the direction (θ,ϕ). (θ,ϕ) is usually unstated; in that case, it is assumed that the source intensity is the maximum over all directions.

Define *source level* as

$$SL(\theta,\phi) = 10 \log [I(\theta,\phi)/I_o],$$

where I_o is the reference intensity (usually that of a plane wave of rms pressure $1\mu Pa$). The reference pressure and reference distance must be specified. The reference direction should be stated if it is not that of maximum intensity.

Source Power

For an omnidirectional source, the power radiated by the projector at range r is $I_r \cdot 4\pi r^2$ where I_r is the radiated intensity at range r (in the far field). If intensity has SI units of W/m^2, then the power has units of W.

The result can be extrapolated to a unit reference distance if either I_1 is known or $I_r = I_1/r^2$. Then the *Source Power* at unit distance is $4\pi I_1$, where I_1 is the intensity at unit distance in units of power/area.

Source Directional Response, Directivity, and Beam Pattern

For an acoustic source, assume source intensity can be expressed as a function $I(\theta,\phi)$ specifying the plane-wave intensity emitted in (vertical, azimuthal) direction (θ,ϕ). The intensity or decibel expression of $I(\theta,\phi)$ is the *source directional response*. Where $I(\theta,\phi)$ is normalized to the value I_o for which $I(\theta,\phi)$ is greatest, then

$$B(\theta,\phi)=I(\theta,\phi)/I_o$$

is the source's *directivity function*. The decibel version is the *beam pattern*. Note that the assumption that the source emissions can be expressed as a sum of plane waves is equivalent to a spatial stationarity (homogeneity) assumption.

For a directional source with intensity radiation pattern $B(\theta,\phi)$, total *Source Power* at unit distance is found from

$$\iint_{\substack{\text{Unit}\\\text{Sphere}}} B(\theta,\phi)\, I(\theta,\phi)\, d\Omega.$$

2.18 Definitions Related To Impulsive Sources And Transient Signals

Peak Pressure

For pressure time series p(t), $0 \le t \le T$, from an impulsive source or of a transient nature, define the *peak pressure* as $P_{max} = \max_{0 \le t \le T} p(t)$. The peak pressure is almost always used to measure maximum positive pressure or peak amplitude.

Impulse

The *impulse* of a force F(t) is defined for the time interval [s, t] during which the force acts as

$$\text{impulse} = \int_s^t F(t)dt,$$

When the integral exists, units are those of force-time (N•s), or can be viewed as

$$\text{mass•acceleration•time} = \text{mass•velocity},$$

with SI units of kg•m/s.

Impulse for Pressure

In the case of a pressure wave, p(t), the *impulse* is defined as

$$\text{impulse} = \int_T p(t)\,dt,$$

where the integral is over the duration of the pressure wave. Commonly used units for *pressure impulse* are Pa•s and psi•ms.

Note that because of the definition of the (acoustic) pressure disturbance, the time-averaged acoustic pressure must be zero. Hence the impulse of the disturbance must also be zero.

Positive Impulse

Weston (1960) and others use *positive impulse* as a characteristic of the pressure field for an explosive source. For pulse p(t) with $p(t) \ge 0$ over $0 \le t \le T$, define

$$\text{positive impulse} = \int_0^T p(t)dt.$$

Common units are Pa•s and psi•ms.

2.19 Energy Metrics

Energy Flux Density

For transient signals from impulsive or other sources, instantaneous intensity will fluctuate and (average) intensity will be sensitive to averaging intervals. Common practice [Urick (1983), Weston

(1960), Cole (1950), Pierce (1989)] is to use an energy (vice power) measure. The natural choice is the *energy flux density* (EFD) defined as:

$$\int_0^T p(t)\,u(t)\,dt$$

where p(t) is the signal pressure, u(t) is the signal particle velocity in the direction of propagation, and [0,T] is the signal duration (T may be ∞). Notice that EFD is the time integral of instantaneous intensity. For plane waves,

$$\mathrm{EFD} = \frac{1}{\rho c}\int_0^T p^2(t)\,dt,$$

where ρc is the impedance. SI units are J/m^2.

Energy Spectrum

For pressure p(t), real and continuous (except for perhaps a finite number of discontinuities of bounded variation) on $-\infty \le t \le \infty$, and satisfying

$$\lim_{T\to\infty}\int_{-T}^{+T}|p(t)|\,dt < \infty.,$$

the Fourier transform of p(t) exists and is defined by

$$\Im_p(f) \equiv \int_{-\infty}^{\infty} p(t)e^{-i2\pi f t}dt \quad \text{for } -\infty < f < \infty.$$

Under these conditions,

$$p(t) = \int_{-\infty}^{\infty} \Im_p(f)e^{i2\pi f t}df \text{ for } -\infty \le f \le \infty,$$

wherever p is continuous.

Define $\dfrac{2|\Im_p(f)|^2}{\rho c}$ as the *energy spectrum* of p(t). It has SI units of $J/(m^2\ Hz)$.

Since p(t) is real,

$$\Im_p(f) = \Im_p^*(-f) \text{ and } |\Im_p(f)|^2 = |\Im_p(-f)|^2.$$

Note that the *energy spectrum* differs from the *power spectrum* in that the latter averages the transform in time. As pointed out, for a time series of finite duration T, the *energy spectrum* has value T times that of the *power spectrum*.

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2.20 Decibels

Following Ross (1987), decibels were originally defined in the 1920's by workers in the electronic communications industry. For two measurements of power, P and Q, the log of the ratio (log P/Q) was given units of *bels*, named after Alexander Graham Bell. Later, to avoid dealing with fractions of bels, workers turned to the decibel (dB):

$$10\log(P/Q).$$

For pressure (or voltage), whose square is proportional to power, the decibel is given by

$$10\log(p^2/p_o^2) = 20\log(p/p_o),$$

where p_o is the reference pressure, usually indicated as 'dB re p_o.'

Thus, for example, an rms pressure of 100 μPa is equal to 40 dB re 1 μPa, or 14 dB re 20 μPa .

Many of the conventions and references derive from early work on human hearing. For example, the standard reference pressure for dBs in atmospheric acoustics is now 20 μPa. The popular standard of the past was 0.0002 μbar = 0.0002 dyn/cm^2 , which equals 20 μPa. The origin of this reference is usually attributed to human hearing tests in which the intensity of a barely audible 1000 Hz tone was measured at 10^{-12} W/m^2. But for impedance in air,

$$10^{-12}\,\mathrm{W/m^2} = \frac{p^2}{\rho c} = \frac{p^2}{415\ \mathrm{kg/m^2 \bullet s}}.,$$

and

$$p = 2.04 \bullet 10^{-5}\,\mathrm{Pa} = 20\ \mu\mathrm{Pa}.$$

The word "level" usually indicates decibel quantity (e.g., SPL, spectrum level). For decibel expression of certain quantities, it is generally true that the reference quantity has the same units as the quantity expressed. However, shortcuts are traditionally taken when stating the reference. Below are some of the more common conventions.

Expression or Quantity	Actual Reference [Example]	Reference in Common Use [Example]
Sound Pressure Level (SPL) $= 10 \log \left(\frac{\text{Pressure}^2}{(\text{Ref. Pressure})^2} \right)$	(Ref. Pressure)^2 [e.g., 1μPa^2 or 1μbar^2]	Ref. Pressure [e.g., 1 μPa, 1 μbar, 20 μPa]
Intensity Level $= 10 \log \left(\frac{\text{Intensity}}{\text{Ref. Intensity}} \right)$	Ref. Intensity [e.g., 1 W/m^2]	Ref. Pressure [e.g., 1 μPa] Interpreted as "relative to the intensity of a plane wave of pressure 1μPa"
Spectrum Level $= 10 \log \left(\frac{\text{Spectral Density}}{\text{Ref. Spectral Density}} \right)$	Ref. Spectral Density = Ref. Pressure^2/(Frequency Band) or Ref. Intensity/Band [e.g., 1μPa^2/Hz]	Ref. Pressure / (Ref. Band) $^{1/2}$ [e.g., 1μPa/√Hz]
Source Level = 10 log (Source Intensity at Reference Distance in Direction of Propagation/Ref Intensity)	Reference Intensity at Ref. Distance, in Direction of Propagation [e.g., 1 W/m^2 at 1 m]	Reference Pressure at Reference Distance [1μPa at 1 m]. As for intensity, the interpretation is of intensity of a plane wave of pressure 1 μPa.
Energy (Flux) Density Level $= 10 \log \left(\frac{\text{Energy Flux Density}}{\text{Ref. Energy Flux Density}} \right)$	Ref. Energy Flux Density = Ref. Pressure^2 Time/Impedance [e.g., 1 (W/m^2)•s]	Reference (Pressure)^2 Time [e.g., μPa^{2}s]

Note that in this series of reports, references in 'common use' will usually be employed.

3.0 SOME TERMS USED FOR NOISE EFFECTS AND SIGNAL PROCESSING

3.1 Pure Tone Signal or Wave (Also, Continuous Wave, CW, Monochromatic Wave, Unmodulated Signal)

Each term means a single-frequency wave or signal. The actual bandwidth of the signal will depend on context, but could be interpreted as "single-frequency as far as can be determined."

3.2 Narrowband Signal

Narrowband is a non-precise term. It is used to indicate that the signal can be treated as a single-frequency carrier signal which is made to vary (is modulated) by a second signal whose bandwidth is smaller than the carrier frequency.

3.3 Frequency Modulated (FM) Signal

A *frequency-modulated* (FM) signal is one in which the dominant modulation of a single-frequency (carrier) signal is the temporal modulation of the carrier frequency. The frequency of an FM signal is expressed as

$$f(t) = f_0 + m(t),$$

where it is usually the case that m(t) varies with frequencies less than f_0.

A *linear FM (LFM) pulse* is a pulse whose frequency varies linearly with time. The frequency of the pulse has form

$$f(t) = f_0 + mt,$$

where f_o is the carrier frequency and m is the frequency slope in Hz/s. The phase of the signal is the integral of the frequency, expressible as

$$\text{phase } (t) = 2\pi(f_0 t + 0.5mt^2).$$

In radar contexts, an LFM signal is often called a *"chirp" pulse or FM slide.*

3.4 Pseudo-Random Noise (PRN) Signal

A *pseudo-random noise* (PRN) pulse can be any irregular pulse whose exact function of time is known. In practice, the PRN is usually random-like in frequency and amplitude within given bounds.

3.5 Impulse Response

In signal processing, an idealized delta-function time series is called an *impulse*. The time series has value zero everywhere except at one point in time. The integral (energy)of the series however is finite, and the spectrum white across the whole band.

For a system which acts on a signal as input and produces an output (communications channel, sonar processor, signal filter, etc.), the *impulse response* is the output of the system resulting from the input of an idealized impulse. If the system response does not change with time, then the impulse response determines the system response to any input signal.

3.6 Effective Bandwidth (Equivalent Bandwidth) of a Signal or Filter

The bandwidth of a signal or filter may be described in several ways. Bendat and Piersol (1971) give three possibilities which cover most of the definitions found in the literature.

Let H(f) denote a linear filter response function or the amplitude spectrum of a signal, and let H_m be the maximum value of H(f).

(A) Define the *half-power bandwidth* as $B_r = f_2 - f_1$ where f_2 and f_1 are the frequencies at which $|H(f_2)|^2 = |H(f_1)|^2 = \frac{1}{2}|H_m|^2$. This definition makes sense for spectra and filters with well-defined maxima and monotonic falloff to the half-power points.

(B) Define the *noise bandwidth*, B_n, as

$$B_n = \frac{\int |H(f)|^2 df}{|H_m|^2}.$$

B_n is defined so that ideal, band-limited white noise with constant spectral density $|H_m|^2$ and bandwidth B_n has the same power as H(f).

(C) Define the *equivalent statistical bandwidth* (*equivalent width* for Blackman and Tukey (1959)) as

$$B_e = \frac{\left[\int_0^\infty |H(f)|^2 \, df\right]^2}{\int_0^\infty |H(f)|^4 df} = \frac{R^2(0)}{\int_{-\infty}^{\infty} |R(t)|^2 dt},$$

where R(t) is the autocorrelation function of the underlying time signal, with

$$|H(f)|^2 = \int R(t)e^{i\omega t}dt, \text{ and } R(\tau) = \int_0^\omega |H(f)|^2 e^{i\omega t} d\omega.$$

This is a very popular definition of bandwidth. If H(f) is the spectrum of white noise limited to the band [0,B], as in the previous definition of B_n, then it is clear that B_e=B.

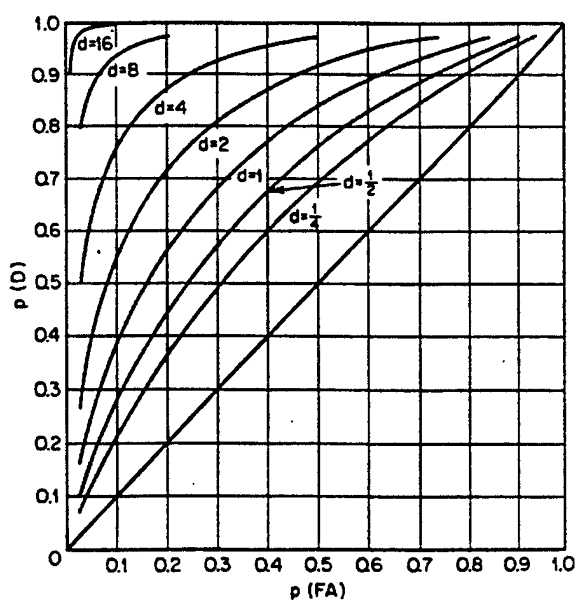
3.7 Effective Time Duration (Equivalent Time Duration) of a Signal or Filter

Just as in the case of bandwidth (3.6), define the *effective time duration* of a signal s(t) as:

$$T_e = \frac{\left[\int_{-\infty}^{\infty} |s(t)|^2 \, dt\right]^2}{\int_{-\infty}^{\infty} |s(t)|^4 \, dt}$$

3.8 Receiver Operating Characteristics (ROC)

(a) Let PD denote Probability of Detection and PFA Probability of False Alarm. For a detection process operating on signal and noise with given characteristics, suppose it is possible to estimate PD as a function of PFA and a parameter, d such that PD = PFA when d=0. Then the function PD = PD(PFA, d) is the ROC. Its plot, with PFA the ordinate, PD the abscissa, and d a level-set index, is usually referred to as the plot of "*ROC Curves*". See sample ROC curve figure from Urick (1983) below.



(b) When the decision process is based on a likelihood test (optimal receiver), there is a formal relationship between the ROC curves and the underlying probabilities. Given conditional probability density functions $f(x|\text{Sig.} + \text{Noise})$ and $g(x|\text{Noise})$, their ratio is the likelihood ratio, r(x). Then, for each value k of r(x),

$$PD = \int_{k}^{\infty} f(x|Sig + Noise)dx,$$

$$PFA = \int_{k}^{\infty} g(x|Noise)dx$$

3.9 Signal-to-Noise Ratio and Signal Differential

Let S and N denote the signal and noise power in the receiver bandwidth (W) at the output of the sensors and at the input of the detection system. Define the *signal-to-noise ratio* as S/N, and the input *signal differential* as 10 log S/N.

3.10 Recognition Differential

Define the *recognition differential* as the value of the signal differential at which the detection occurs with probability 0.5. A false alarm probability must also be prescribed. (after Bartberger, 1965).

(a) "The level of signal-to-noise into the signal processor for which the probability of detection is 50% is called the detection threshold, DT, or recognition differential, NRD, of the processor." Ross (1987)

(b) "In the literature, the signal-to-noise ratio for auditory detection is frequently called recognition differential. This term is defined as the 'amount by which the signal level exceeds the noise level presented to the ear when there is a 50 percent probability of detection of the signal.' Because there is no specification concerning false alarms, the term ...is quantitatively almost meaningless." (Urick, 1983)

3.11 Detection Threshold

"...*detection threshold* is defined as the ratio, in decibel units, of the signal power (or mean-squared voltage) in the receiver bandwidth to the noise power...in a 1-Hz band, measured at the receiver terminals, required for detection at some preassigned level of correctness of the detection process." (Urick, 1983)

3.12 Signal Excess

Signal Excess is defined as

$$SE = 10 \log (S/N) - \text{Recognition Differential}$$

It is thus the decibel amount by which the signal-to-noise ratio exceeds the amount required for 0.5 detection probability at a specified false alarm probability. (Ross, 1987)

3.13 Detection Index

The *detection index,* d, is the parameter in a ROC function which indicates the level of indifference (d=0, PD=PFA) and levels of increasing decisiveness as d increases. For "certain processes and conditions, d is functionally related to the signal-to-noise ratio at the processor output.

3.14 Hearing Threshold

"The *threshold of hearing* is defined as the sound pressure at which one, listening with both ears in a free field to a signal of waning level, can still just hear the sound, or if the signal is being increased from a level below the threshold, can just sense it." (Magrab, p.29, 1975)

"A threshold of audibility for a specified signal is the minimum effective sound pressure of that signal that is capable of evoking an auditory sensation (in the absence of noise) in a specified fraction of trials." (Beranek, p. 394, 1986)

An entire chapter of the textbook of Green and Swets (1973) is dedicated to the theory and measurement of thresholds of hearing.

3.15 Critical Ratio (Hearing)

Current usage for marine animals is as follows (see, e.g., Au, 1993).

For a tonal signal in white noise, the *critical ratio* is the level of the signal-to-noise ratio for which the signal is at hearing threshold level and the noise is taken as the level in a one-hertz band. In underwater sound, this is similar to the definition of recognition differential or detection threshold.

Since the noise power is normalized to a 1-Hz band, the critical ratio is sometimes interpreted as the noise band level which is required to mask the signal. If the noise is white, the noise band level determines a bandwidth, often compared to or treated like a critical band.

3.16 Critical Band (Hearing)

Fletcher proposed the concept of *critical bandwidths* in 1940. (Fletcher, 1940)

"In detecting a tone in the presence of noise, the hearing mechanism appears to reject the noise outside the *critical band* centered on the pure tone, thereby making it appear to behave as a filter set." (after Beranek, 1986)

Zwicker et al. (1980) derived an empirical expression for critical bandwidths based on human hearing data:

$$W(f_c)=25 + 75\{1 + 1.4(f_c/1000)^2\}^{0.69} \text{ Hz},$$

where f_c is the (geometric) center frequency in hertz.

$$W(100) = 100 \quad (100\% \text{ band})$$
$$W(1000) = 160 \quad (16\% \text{ band})$$
$$W(10000) = 2300 \quad (23\% \text{ band})$$

Notice that these bands resemble 1/3 octave bands (23% bands) only at the highest frequencies.

Kinsler and Frey (1962) point out:

> "The critical bandwidth apparently is reached when it includes all frequencies in the noise that excite the same region of the basilar membrane as does the pure tone being masked. The addition of noise outside the critical band may be unpleasant but it does not increase the masking of the pure tone."

and

> "A second and very important characteristic associated with the concept of critical band masking is that the normal threshold of audibility of the masked tone is raised to the decibel level of the critical band, i.e., the band level of the noise in a critical band."

3.17 Temporary (Hearing) Threshold Shift (TTS)

"The diminution, following exposure to noise, of the ability to detect weak auditory signals is termed *temporary threshold shift* (TTS), if the decrease in sensitivity eventually disappears..." (Magrab, 1975)

3.18 Permanent (Hearing) Threshold Shift (PTS)

"The diminution, following exposure to noise, of the ability to detect weak auditory signals is termed *temporary threshold shift* (TTS), if the decrease in sensitivity eventually disappears, and noise-induce (sic) permanent threshold shift (NIPTS) if it does not [eventually disappear]." (Magrab, 1975)

3.19 Weighted Sound Levels

For sound pressure measurements in air related to hearing, it is common practice to weight the spectrum to reduce the influence of the high and low frequencies so that the response is similar that of the human ear to noise. *A-weighting* is the most common filter, with the weight resembling the ear's responses. Other popular weightings are B and C. The table below gives a sampling of the filter values for selected frequencies.

Frequency (Hz)	A-Weighting (dB)	B-Weighting (dB)	C-Weighting (dB)
10	-70	-38	-14
20	-50	-24	-6
40	-35	-14	-2
80	-23	-7	-1
160	-13	-3	0
320	-7	-1	0
640	-2	0	0
2000	+1	0	0
5000	+1	-1	-1
10,000	-3	-4	-4
12,000	-4	-6	-6
20,000	-9	-11	-11

Decibel levels based on these weighted are usually labeled: dBA or dB(A) for A weighting, etc.

3.20 Sound Exposure Level (SEL)

For a time-varying sound pressure p(t), *sound exposure level* is computed as

$$\mathrm{SEL} = 10 \log \left[\frac{1}{t_0} \int_0^T p^2(t)\,dt \Big/ p_0^2 \right],$$

where t_0 is 1 second, T is the total duration of the signal (in the same units as those of t_0, namely seconds) and p_0 is the reference pressure (usually 20 μPa).

SEL is thus a function of p(t), T, and the reference pressure. When the impedance of the medium of interest is approximately constant, then SEL can be viewed as the total energy level for the time interval from 0 to T. It has explicit reference units of p_0 for pressure with implicit units of seconds for time.

When p(t) is A-weighted, then the measure is called the *A-weighted SEL* or *ASEL*. Likewise for other weightings.

3.21 Equivalent Sound Level (L_{eq})

The *equivalent sound level (L_{eq})* is defined as the A-weighted sound pressure level (SPL) averaged over a specified time period T. It is useful for noise that fluctuates in level with time. L_{eq} is also sometimes called the *average sound level (L_{AT}),* so that $L_{eq} = L_{AT}$. (see, e.g., Crocker, 1997)

If $p_A(t)$ is the instantaneous A-weighted sound pressure and p_{ref} the reference pressure (usually 20 μPa), then

$$L_{eq} = 10 \log \left\{ \left(\frac{1}{T} \int_0^T p_A{}^2(t)\,dt \right) \Big/ p_{ref}^2 \right\}.$$

It is thus equivalent to an average A-weighted intensity or power level.

Note that since the averaging time can be specified to be anything from seconds to hours, L_{eq} has become popular as a measure of environmental noise. For community noise, T may be assigned a value as high as 24 hours or more.

3.22 Day-Night Level (L_{dn} or DNL)

Following Magrab (1975), L_{dn} was introduced by the EPA in 1974 to provide a single-number measure of community noise exposure over a specified period. It was designed to improve L_{eq} by adding a correction of 10 dB for nighttime levels to account for increased annoyance to the population.

L_{dn} is calculated as a weighted average of intensities:

$$10^{L_{dn}/10} = (0.625)10^{L_d/10} + (0.375)10^{(L_n+10)/10}$$

4.0 SOME FUNDAMENTAL EQUATIONS OF LINEAR AND NONLINEAR ACOUSTICS

In treating sound transmission from sources in air to receivers in air, at the air-sea interface, and in the water column, we must deal with a range of boundary conditions and several variations on the basic equations for wave propagation. It is important to know the assumptions and conditions that lead to the use of one set of equations or another.

Consider, for example, that in treating the acoustics of aircraft noise we need to account for the effects of:

(a) changing sound speeds and densities of the medium with altitude, time, location,
(b) moving medium (winds, turbulence) at speeds a significant fraction of the sound speed,
(c) severe impedance mismatch at interfaces between air and ground, structures, water,
(d) non-linearities in the form of shock waves, with finite amplitudes and supersonic wave speeds.

In water, on the other hand, the emphasis is quite different, with such features as:

(a) negligible effects of moving media (currents, circulation),
(b) nearly constant density and maximum sound speed changes of a few percent,
(c) waveguide propagation with complex boundary reflection, transmission and scatter,
(d) the possibility of very long range propagation, at lower frequencies
(e) important boundary, shear and lateral wave effects.
(f) rare and short-lived occurrences of finite amplitudes and shock waves

For air-to-water transmission, the effects of the rough sea surface, waves and bubbles are additional concerns.

Condition	**Important for Air**	**Important for Water**
Shock Waves	Sonic Booms	Nearby Explosions
Impedance Mismatch	Air-Ground/Structures	Ocean Surface, Bottom
Moving Medium	Winds	Currents (Not usually very Important)
Density Changes	Large in Air	Minimal in Water
Sound Speed Changes	Large in Air	Small, but Important
Long Range Propagation	Tens of Miles	Hundreds of Miles

The pages that follow illustrate how different conditions can lead to different forms of the 'wave equation,' and hence to different solutions and degrees of difficulty.

4.1 <u>Types of Media and Disturbances</u>

Media encountered in the study of sound include gases, liquids and solids, with a wide range of properties, the single common property for sound wave propagation being elasticity. Governing equations for sound propagation through these media depend on these properties. For example, the usual wave equation (d'Alembert's) encountered in atmospheric and underwater acoustics applies only under highly restrictive conditions, and seldom can similarly compact, single statements be found for more complex problems. When defining "acoustic pressure" or "linear acoustics" or "small amplitude disturbances," it is important to identify just what equations are being solved and what assumptions about the medium and the disturbance go with them.

This section outlines some of the more important cases, considering such properties of the ambient (undisturbed) medium as:

- Elasticity
- Compressibility
- Dissipation (Viscosity, Heat Transfer)
- Ability to Support Shear Stresses
- Spatial and Temporal Properties of the Ambient Medium (e.g., Homogeneity, Stationarity)
- Flow (Homogeneous, Stratified, Stationary, Irrotational, Turbulent)
- State (Adiabatic, Constant Entropy, etc.)

For different types of media, disturbances propagate according to different laws of physics. Mathematical descriptions of how the disturbance propagates depend on additional assumptions and approximations about the disturbances themselves. Two of the most common ones are:

> *Linearized Equations.* All aspects of the disturbance are small compared to those of the medium's ambient state, so that the governing equations can be simplified or linearized, and sometimes called the 'acoustics approximation.'
>
> *Simplified Non-Linear Equations.* Certain properties of the disturbance are allowed to be large, and non-linear equations required, but simplified.

Many books and thousands of papers have been written about the equations of linear and non-linear acoustics. Our purpose here is to list some of the more popular problems, and to supply references about solutions. All of this is important when investigating acoustic problems involving shock waves, winds and currents, shear, turbulence, finite amplitude effects, etc.

Note that only a few problems have the types of "wave equations" (d'Alembert's) to which we are accustomed, and that systems of equations are more common.

We begin with some notation, and then proceed through several sets of acoustic equations.

4.2 Notation

	Pressure	**Velocity**	**Density**	**Entropy**	**Temperature**
Properties of the Ambient Medium	p_o	v_o	ρ_o	s_o	T_o
Properties of Disturbed Medium	$\hat{p}$	$\hat{v}$	$\hat{\rho}$	$\hat{s}$	$\hat{T}$
Changes in Properties Related to the Disturbance	$p = \hat{p} - p_0$	$v = \hat{v} - v_0$	$\rho = \hat{\rho} - \rho_o$	$s = \hat{s} - s_o$	$T = \hat{T} - T_0$

Time = t, Acceleration of Gravity = g, Sound Speed = c

Vectors are represented by bold-faced letters, scalars by non bold-faced letters.

∇ denotes both the divergence and gradient operators with $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$.

For a given velocity **v**, D/Dt represents the Stokes operator.

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v} \bullet \nabla \ .$$

4.3 Fluid Dynamics Equations for an Ideal Fluid

Ideal Fluid: Define the "*Ideal Fluid*" as one which has no dissipation from viscous stresses or the effects of heat conduction (Cole, 1948).

Conservation of Mass (Continuity Equation)

Within an ideal fluid, select any small, fixed volume. Whether there is a disturbance of the fluid or not, any change in mass of fluid within the fixed volume must equal the net quantity of fluid which flows through the surface of the boundary. Any such changes are caused by motion in the fluid.

When the ideal fluid is further restricted to have smoothly changing velocity and density (differentiably smooth), then the *Equation for Conservation of Mass* (also, *Continuity Equation*) is given by:

$$\frac{\partial \hat{\rho}}{\partial t} + \nabla \bullet (\hat{\rho}\, \hat{\mathbf{v}}) \quad = \quad 0.$$

An alternative, equivalent statement, derived by Euler using a small volume moving with the fluid, is expressed as

$$\frac{D\hat{\rho}}{Dt} + \hat{\rho} \nabla \bullet \hat{\mathbf{v}} \quad = \quad 0.$$

In both cases, ρ is fluid density in the small volume, **v** the fluid velocity in the volume.

Conservation of Momentum (Equation of Motion) (Euler's Equation of Motion)

From Newton's second law (net forces are zero), the ideal fluid must satisfy

$$\hat{\rho} \frac{D\hat{\mathbf{v}}}{Dt} + \nabla \hat{p} = \mathbf{0}.$$

where $\hat{p}$ is fluid pressure, $\hat{\rho}$ density, $\hat{v}$ velocity, ∇ the divergence operator, $\frac{D}{Dt}$ the Stokes operator. Again, the existence of the derivative requires smooth changes in $\hat{v}$ and $\hat{\rho}$.

Conservation of Energy:

For an ideal fluid, let E denote the "internal" energy per unit mass of a small volume within an ideal fluid. E is the sum of the thermal and chemical energies. Then, under an assumption of differentiability,

$$\hat{\rho}\frac{D}{Dt}\left(E+\frac{1}{2}\hat{v}\bullet\hat{v}\right)=-\nabla\bullet(\hat{p}\hat{v}).$$

A more useful version uses the Equations of Conservation of Mass and Momentum to yield:

$$\hat{\rho}\frac{DE}{Dt}=\frac{\hat{p}}{\hat{\rho}}\frac{D\hat{v}}{Dt}.$$

Equation of State

Because neither viscosity nor heat effects are considered for the ideal fluid, all changes in the physical state of an element of fluid must take place at constant entropy $(\hat{S})$, or

$$\frac{d\hat{S}}{dt}=0.$$

Equivalently, density changes caused by applied pressure take place adiabatically. Cole notes that the law is local in space and time, depending on previous events.

The functional dependence $\hat{p}(\hat{\rho})$ can in some cases be estimated from data (after Cole 1948).

4.4 Summary of Fluid Dynamic Equations for General "Ideal Fluid"

For the general ideal, flowing fluid, there is no single 'wave equation.'

Properties of Medium ("Ideal Fluid"):

- Elastic, Compressible, Non-Dissipative, Unable to Support Shear when Static.
- State: No dissipation or heat effects for ideal fluid. Hence, dS/dt = 0 where S is entropy. Density changes caused by pressure take place adiabatically.
- Flow: Deterministic.

Fluid Dynamics Equations (e.g., Pierce 1995):

Continuity (Conservation of Mass): $\dfrac{\partial\hat{\rho}}{\partial t}+\nabla\bullet(\hat{\rho}\,\hat{\mathbf{v}})=\dfrac{\partial\hat{\rho}}{Dt}+\hat{\rho}\nabla\bullet\hat{\mathbf{v}}=0.$

Motion (Conservation of Momentum): $\hat{\rho}\dfrac{D\hat{\mathbf{v}}}{Dt}+\nabla\hat{p}+g\hat{\mathbf{u}}=0.$

Energy: $\hat{\rho}\dfrac{D\hat{E}}{Dt}=\dfrac{\hat{p}}{\hat{\rho}}\dfrac{D\hat{\mathbf{v}}}{Dt}.$

State: $\dfrac{d\hat{S}}{dt}=0.$

$$\frac{d\hat{p}}{d\hat{\rho}}=\left(\frac{\hat{p}}{\hat{\rho}^2}-\frac{\partial\hat{E}}{\partial\hat{\rho}}\right)\Big/\left(\frac{\partial\hat{E}}{\partial\hat{p}}\right),\text{ with }\hat{p}(\hat{\rho})\text{ known from data.}$$

Wave Equation: No equivalent 'wave equation.'

Application: Non-linear (finite amplitude) acoustics problems such as for sonic booms and explosions in air or water.

4.5 Linearized Equations (First Order Approximations) for Non-Viscous Ideal Fluid

"Linear Acoustics Approximation"

$$\frac{D\mathbf{v}}{Dt}+(\mathbf{v}\bullet\nabla)\mathbf{v}_0+\frac{1}{\rho_0}\nabla p+\frac{p}{(\rho_o c)^2}\nabla p_0=0$$

$$\frac{Dp}{Dt}+\mathbf{v}\bullet\nabla p_0+c^2 p\nabla\left(\frac{\mathbf{v}_0}{c^2}\right)+\rho_0 c^2\nabla\bullet\mathbf{v}=0.$$

Applications: General linear acoustics problems for non-homogeneous media with flow.

4.6 Linear Equations for Ideal Homogeneous Fluid With Constant Velocity Flow

Wave Equation (e.g., Pierce 1995):

$$\nabla^2 p-\frac{1}{c^2}\left(\frac{\partial}{\partial t}+\mathbf{v}_o\bullet\nabla\right)^2 p=0.$$

Applications: Short-range (constant sound speed and density), linear acoustic propagation in air with steady wind. Most approaches to solution are based on approximations, some with sound speed modified to partially account for flow.

4.7 Linear Equations for Homogeneous, Unmoving Ideal Fluid

Wave Equation:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0.$$

Related Equations:

If $\nabla \times \mathbf{v} = \mathbf{0}$ (irrotational medium), then there exists Φ such that $\mathbf{v} = \nabla\Phi$ and $p = -\rho_0 \frac{\partial \Phi}{\partial t}$.

Applications: Wave equation for simplest problems - no flow and nearly constant sound speed and density. Analytic solutions exist for simple boundary conditions. For single frequency, Helmholtz elliptic equation has many types of solutions, including normal mode and ray approximations.

4.8 Linear Equations for Ideal Time-Constant Fluid, No Flow

Wave Equation:

$$\rho\nabla \bullet \left(\frac{1}{\rho}\nabla p\right) - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0.$$

Applications: Familiar wave equation for underwater sound, with no time variability in the medium, but with spatially variable density and sound speed. Approaches include single-frequency simplification to Helmholtz equation, coupled normal modes, parabolic equation approximations, ray approximations, adiabatic rays and modes.

4.9 Linear Equations for Inhomogeneous Ideal Fluid With Steady (Irrotational) Flow and Constant Entropy

Wave Equation (Pierce 1995):

$$\frac{1}{\rho}\nabla \bullet (\rho\nabla\Phi) - \frac{D}{Dt}\left[\frac{1}{c^2}\frac{D}{Dt}\Phi\right] = 0, \quad \text{where } p = -\rho\frac{D}{Dt}\Phi.$$

Applications: Linear acoustics problems in air with steady flow (wind), and space/time variability in sound speed and density.

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APPENDIX A. INTERNATIONAL SYSTEM OF UNITS (SI)

The International System of Units or SI (System International d'Unites) was established in 1960 and is recognized as the standard throughout the world. In the United States, both the American National Standards Institute (ANSI) and the Department of Defense have adopted SI. Information about SI is published by technical societies, as, for example, by the American Institute of Physics in its August issue each year.

The SI has seven **base units** from which all other units are derived. The base units are as follows:

Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electrical Current	ampere	A
Thermodynamic Temperature	kelvin	K
Amount of Substance	mole	mol
Luminous Intensity	candela	cd

Units derived from the seven base units usually have SI-sanctioned names. Examples of **SI derived units** relevant to this report are given below:

Derived Quantity	Equivalent SI Quantities	Derived Unit (Symbol)	Equivalent SI/ Derived Units
Speed	Length/Time	---	m/s
Acceleration	Length/(Time)^2	---	m/s^2
Area	Length^2	---	m^2
Volume	Length^3	---	m^3
Force	Mass • Acceleration	Newton (N)	N = kg•m/s^2
Pressure	Force/Area = Mass/(Length • Time^2)	Pascal (Pa)	Pa = N/m^2 = kg/m•s^2
Work, Energy, Heat	Force • Length = Mass • Length^2/Time^2 = (Pressure • Area) Length = Power • Time	Joule (J)	J = N•m = kg•m^2/s^2 = Pa•m^3 = (J/s)s = W•s
Power	Energy/Time = Force • Length/Time = Mass • Length^2/Time^3 = (Pressure • Area) • Length/Time	Watt (W)	W=J/s = N•m/s = kg•m^2/s^3 = Pa•m^3/s
Energy Flux Density	Energy/Area = (Power/Area) • Time = Pressure • Length = Intensity • Time	---	J/m^2 = (W/m^2)s = Pa•m = [Pa^2/(Pa•s/m)]s
Acoustic Intensity	Pressure • Speed = (Force/Area) • Speed = Power/Area	---	Pa•m/s = (N/m^2)(m/s) = W/m^2
Plane Wave Intensity	(Pressure)^2/Impedance = Power/Area	---	Pa^2/Pa•s/m) = Pa•m/s = W/m^2
Density	Mass/Volume	---	kg/m^3
Characteristic Impedance	Density • Speed = Mass/Length^2 • Time = (Force/Acceler.)/Length^2 • Time = (Force/Length^2) • (Time/Length) = (Pressure)/(Speed)	---	(kg/m^3)(m/s) = kg/m^2•s = (N/m/s^2)/(m^2•s) = (N/m^2)(s/m) = (Pa)/(m/s)
Energy Flux Density Spectrum	(Energy/Area)/Frequency = (Power/Area)(Time/Frequency) = (Intensity)(Time/Frequency) = Pressure•Length/Frequency = Force/(Length•Frequency)	---	(J/m^2)/Hz = (W/m^2)(s/Hz) = (Pa•m/s)(s/Hz) = (Pa•m)/Hz = N/m•Hz

APPENDIX B. KEY RELATIONSHIPS

This appendix provides formulas relating units for various metrics used in acoustics. These relationships are often useful in themselves, but are presented in tables for ready conversion in Appendix C.

SECTION	QUANTITY
B-1	TIME
B-2	LENGTH
B-3	VELOCITY (SPEED)
B-4	AREA
B-5	VOLUME
B-6	MASS
B-7	DENSITY
B-8	FORCE
B-9	ENERGY
B-10	IMPULSE

SECTION	QUANTITY
B-11	POWER
B-12	PRESSURE
B-13	ACOUSTIC IMPULSE
B-14	ACOUSTIC IMPEDANCE
B-15	ACOUSTIC INTENSITY
B-16	ACOUSTIC ENERGY FLUX DENSITY
B-17	ACOUSTIC POWER SPECTRUM
B-18	ACOUSTIC ENERGY SPECTRUM
B-19	AIR/WATER RELATIONSHIPS

B-1. TIME

1 ms = 1000 μS	1 s = 1000 ms	1 min = 60 s	1 hr = 60 min	1 day = 24 hours

B-2. LENGTH

1 mm = 107 Angstrom (Å)	1 fathom = 2 yds = 1.829 m
1 cm = 10 mm = 0.3937008 inches	1 kyd = 1000 yds = 914.4 m
1 m = 100 cm = 39.37008 inches = 3.28084 ft	1 statute mile = 5280 feet = 1760 yd
1 km = 1000 m = 1093.613 yds = 0.6213712 miles	1 statute mile = 1 mile = 1.61 km
1 in = 2.54 cm = 25.4 mm	1 nmi = 1.15 statute mile
1 ft = 12 in = 30.48 cm = 0.3048 m	1 nmi = 2025.4 yds = 6076.1 ft = 1852 m
1 yd = 3 ft = 91.44 cm = 0.9144 m	

B-3. VELOCITY (SPEED)

1 ft/s = 60ft/min = 3600 ft/hr	1 knot = 1.852 km/hr = 101.269 ft/min
1 mph = 1.4667 ft/s = 1.6093 km/hr = 0.447 m/s	1 m/s = 3.6 km/hr = 3.2808 ft/sec = 196.85 ft/min
1 knot = 1 nmi/hr = 1.1515 mph	1 m/s = 1.94384 knots
1 knot= 1.6878 ft/s = 0.51444 m/s	

B-4. AREA

1 in^2 = 6.4516 cm^2	1 km^2 = 10^6 m^2 = 1.196 10^6 yd^2
1 m^2 = 10000 cm^2 = 1.19599 yd^2	1 km^2=0.386 $miles^2$ = 0.292 nmi^2
1 ft^2 = 144 in^2 = 929.03 cm^2	1 $(nmi)^2$ = 4.102 10^6 yd^2 = 3.43 km^2
1 yd^2 = 9 ft^2 = 0.8361 m^2	1 $mile^2$ = 3.098 10^6 yd^2 = 2.59 km^2
1 acre = 43,560 ft^2 = 4046.86 m^2	

B-5. VOLUME

1 in^3 = 16.387 cm^3	1 yd^3 = 27 ft^3 = 46656 in^3	1 qt. (liquid) = 57.75 in^3
1 in^3 = 0.016387 liter	1 m^3 = 10^6 cm^3 = 1.308 yd^3	1 liter = 1000.028 cm^3
1 ft^3 = 1728 in^3	1 gal. = 231 in^3	1 liter = 61.03 in^3
1 ft^3 = 0.0283 m^3	1 fluid oz = 1.80469 in^3	1 liter = 0.03532 ft^3

B-6. MASS

B-6a. Notes On Mass And Weight

The *weight* of a body means the gravitational force exerted on it by the earth. Thus, the weight may vary with distance from the ground. Since weight is a force, it should be measured as such and have units of force: namely, newtons (N), dynes (dyn), or pounds (lb).

Newton's equation provides the relationship between the weight and mass of a body:

$$\text{mass} = \text{weight}/(\text{acceleration of gravity}) = \text{weight}/g.$$

The SI unit of mass is the kg, and the SI unit of force is the newton (N). Hence, weight (force) of a 1 kg mass on earth is 1(kg)(9.8 m/s^2) = 9.8 N.

The english unit of mass is the slug and the english unit for force (or weight) is the pound (force). The weight of one slug on earth is 1 (slug)(32 ft/s^2) = 32 lb, where the slug has been defined as 1 slug = 1 lb (force)/(ft/s^2).

The weight of a 0.4536-kg mass on earth is 4.448 N and the weight of a 0.0313-slug mass on earth is 1 lb (force). Since 1 lb (force) = 4.448 N, 0.4536 kg (mass) = 0.0313 slug, or

$$1 \text{ kg} = 0.0685 \text{ slug and } 1 \text{ slug} = 14.6 \text{ kg}.$$

The slug is seldom used in practice for the unit of mass. Instead, the pound is used for both mass and force. This can cause some confusion (especially when gravity is not that of sea level on earth). The usual convention is to define the pound (mass) in terms of the kg:

$$1 \text{ lb (mass)} = 0.4536 \text{ kg (mass)}$$

Then

$$1 \text{ lb (weight)} = 4.448 \text{ N} = 4.448 \text{ kg (m/s}^2)$$
$$= 1 \text{ lb (mass) (32 ft/s}^2)$$

It is also occasionally the case that the kg is used as a measure of force (or weight) in the metric system. In that case,

$$1 \text{ kg (weight)} = 9.8 \text{ N} = 1 \text{ kg (mass) (9.8 m/s}^2).$$

B-6b. MASS

1 kg (mass) = 0.0685 slug	1 kg = 1000 g	1 kg (mass) = 2.205 lb (mass)
1 slug = 14.6 kg	1 lb (mass) = 16 oz. (mass)	1 lb (mass) = 0.4536 kg (definition)
1 slug = 1 lb(force)•s^2/ft	1 T. (mass) = 2000 lb (mass)	
1 g = 437.5 grain (gr)	1 metric T. 1000 kg	

B-7. DENSITY

DENSITY = MASS/VOLUME	
1 g/cm^3 = 1000 g/liter	1 kg/m^3 = 3.613 10^{-5} lb (mass)/in^3
1 g/cm^3 = 1000 kg/m^3 = 1 metric ton/m^3	1 lb (mass)/gal. = 7.480519 lb (mass)/ft^3
1 lb (mass)/in^3 = 1728 lb (mass)/ft^3	1 g/liter = 1 kg/m^3
1 lb (mass)/ft^3 = 0.0160185 g/cm^3	1 slug/m^3 = 14.6 kg/m^3

**(see notes on mass and weight)

B-8. FORCE

FORCE = MASS × ACCELERATION	1 lb (weight) = 4.448 N = 0.454 kg (weight)
1 N = 1 kg•m/s^2 = 10^5 dyn = 10^5 g•cm/s^2	1 lb (weight) = 16 oz (weight)
1 kg (weight) = 9.81 kg•m/s^2	1 T. = 2000 lb
1 erg/cm = 1 g•cm/s^2 = 1 dyn	1 kg (weight) = 2.205 lb (definition)
1 kg (weight) = 1000 g (weight)	

**(see notes in section B-6.1 on mass and weight)

B-9. ENERGY (WORK)

ENERGY = FORCE × DISTANCE	1 erg = 1 dyn•cm	1 ft-lb = 5.0505 10^{-7} hp•hr
1 J = 1 N•m = 1 kg•m^2/s^2	1 kW•hr = (3.6) 10^6 J	1 ft-lb = 3.76616 10^{-7} kW•hr
1 J = 10^7 g•cm^2/s^2 = 1 W•s	1 ft-lb = 1.355818 J	1 ft-lb = 1.2851 10^{-3} Btu
1 J = 0.239 cal	1 ft-lb = 0.01338 liter-atm	1 ft-lb = 0.32383 calories.
1 erg = 1 g•cm^2/s^2 = 10^{-7}J		

B-10. IMPULSE

IMPULSE = FORCE × TIME	1 N•s = 0.2248 lb(force)•s
IMPULSE = MASS × VELOCITY	1 dyn•s = 1 erg•s/cm = 1 g•cm/s
1 N•s = 1 kg•m/s	1 lb (force) •s = 4.45 N•s
1 N•s = 10^5 dyn•s	1 lb (force)•s = 0.45 kg (weight)•s

B-11. POWER

POWER = ENERGY/TIME = WORK/TIME	1 hp = 745.7 W ≈ (120 volts)(6 amps)
POWER = FORCE × DISTANCE/TIME	1 Btu/min = 17.5844 W
1 W = 1 J/s = 1 N•m/s = 1 kg•m^2/s^3	1 cal/sec = 4.1868 W
1 W = 10^7 erg/s	1 cal/min = 0.06978 W
1 erg/s = 1 dyn•cm/s = 1 g•cm^2/s^3	1 ft-lb/s = 1.356 W
1 hp = 550 ft-lb/s	

Note that 1 *horsepower (hp)* is the power required to raise 33,000 pounds one foot in one minute. Hence,
1 hp (in units of: force × distance/time) = (33000 lbs) × (1 ft)/(1 minute) = 550 ft-lb/s

B-12 PRESSURE

B-12a PRESSURE

PRESSURE = FORCE/AREA	1 bar = 29.5 in Hg = 14.5 psi = 2088 psf
1 Pa = 1 N/m^2 = 1 J/m^3 = 1 kg/m•s^2	1 psf = 0.00694 psi = 4.758•10^7.µPa
1 Pa = 10^6 µPa = 10 dyn/cm^2 = 10 µbar	1 atm = 14.69595 psi = 1.013•10^{11} µPa
1 µPa = 0.05•(20 µPa)	1 atm = 1.01325 bar = 0.1021 psf
1 µPa = 10^{-5} dyn/cm^2 = 1.4504•10^{-10} psi	1 psi = 144 psf = 6.895•10^9 µPa
20 µPa = 0.0002 µbar = 2.9•10^{-9} psi	1 psi = 3.4474•10^8 (20 µPa)
1 kPa = 1000 Pa = 10^9 µPa = 0.145 psi=20.88 psf	1 psi = 6.895 kPa = 0.068 atm (6.9) 10^4 dyn/cm^2
0.0002 µbar = 0.0002 dyn/cm^2 =20 µPa	1 mm Hg = 133.3 Pa
1 µbar = 0.1 Pa = 1 dyn/cm^2= 1.4504•10^{-5} psi	1 in Hg = 0.491 psi

B-12b. Sound Pressure Level

For pressure p, the *sound pressure level* (SPL) is defined as follows:

$$SPL = 20 \log (|p| / p_0) \text{ dB re } 1\ p_0,$$

where p_0 is the reference pressure (usually 1 µPa or 20 µPa or 1 µbar).

If $\quad$ SPL = X dB re 1 μPa, then

SPL = (X–26) dB re 20 μPa and SPL = (X–100) dB re 1 μbar.

Other relationships:

SPL = Y dB re 20 μPa = (Y+26) dB re 1μPa = (Y–171) dB re 1 psi
= (Y–128) dB re 1 psf.

For example, if the pressure is 1 psi, then

SPL = 0 dB re 1 psi = 197 dB re 1 μPa = 171 dB re 20 μPa
= 43 dB re 1 psf = 97 dB re 1 μbar.

B-13. ACOUSTIC IMPULSE

IMPULSE = PRESSURE × TIME	1 psi•ms = 1000 psi•μs
1 Pa•s = 0.001 kPa•s = 1000 Pa•ms = 1 kPa•ms	1 psi•s = 1000 psi•ms = 6895 Pa•s
1 kPa•s = 10^9 μPa•s = 10^{12} μPa•ms	1 psi•ms = 144 psf•ms
1 kPa•ms = 10^6 μPa•s	1 psi•s = 6.895 kPa•s
1 psi•ms = 6.895 Pa•s	

B-14 ACOUSTIC IMPEDANCE

Acoustic Impedance = Density × Sound Speed = (Mass/Volume) × (Length/Time)
= (Mass/Area) × (1/Time) = (Weight)/(Gravity × Area × Time) = (Pressure)/Speed

B-14A. ACOUSTIC IMPEDANCE FOR WATER:

Water *Density* (4°C) = $\rho_w \approx 1$ g/cm^3 = 10^3 kg/m^3 ≈ 1.94 slug/ft^3 ≈ 62.43 lb (mass)/ft^3

Sound Speed = $c_w \approx$ 1500 m/s = $1.5 \cdot 10^5$ cm/s ≈ 4920 ft/s ≈ 59040 in/s

Impedance of Water = $\rho_w c_w \approx 1.5 \cdot 10^6$ kg/s•m^2 = $1.5 \cdot 10^6$ rayl = $1.5 \cdot 10^5$ g/s•cm^2
= $1.5 \cdot 10^{12}$ μPa•(s/m) = $1.5 \cdot 10^5$ (dyn/cm^2)(s/cm) ≈ 9544.8 slugs/ft^2•s
≈ $3.072 \cdot 10^5$ lb(mass)/ft^2•s

B-14B. ACOUSTIC IMPEDANCE FOR AIR:

Standard *Density of Air* (Sea Level, 15°C) = ρ_a ≈ 1.225 kg/m^3 ≈ 0.0839 slug/m^3
≈ 0.00237 slug/ft^3 ≈ 2.701 lbs(mass)/m^3
≈ 0.0764 lb(mass)/ft^3

Nominal *Sound Speed in Air* (Sea Level, 0 C°) = $c_a \approx$ 344 m/s = $3.44 \cdot 10^4$ cm/s = 1128.6 ft/s

Impedance of Air = $\rho_a c_a \approx$ 421.4 kg/s•m^2 = 421.4 rayl = 42.14 (dyn/cm^2)•(s/cm)
= $4.214 \cdot 10^8$ μPa•(s/m) ≈ 2.674 slug/ft^2•s ≈ 86.804 lb(mass)/ft^2•s

B-14c. COMPARISON OF IMPEDANCES IN AIR AND WATER

Sound Speed Ratio = $c_w/c_a \approx 4.36$

Density Ratio = $\rho_w/\rho_a \approx 816.33$

Impedance Ratio = $\rho_w c_w / \rho_a c_a \approx 3559.6$

Impedance Ratio (dB) = $10 \log (\rho_w c_w / \rho_a c_a) \approx 10 \log (3559.6) \approx 35.5$ dB

B-15. ACOUSTIC INTENSITY

B-15a. ACOUSTIC INTENSITY

INTENSITY = PRESSURE × VELOCITY	1 W/m^2 = 10^3 dyn/cm s
INTENSITY = PRESSURE^2/IMPEDANCE	1 W/cm^2 = 10^4 W/m^2 = 10^7 erg/cm^{2}s
1 W/m^2= 1 J/(s•m^2) = 1 N/m•s = 1 Pa•(m/s)	1 lb/ft s = 14.596 J/m^{2}s = 14.596 W/m^2
1 W/m^2 = 10^6 μPa•(m/s)	1 hp/m^2 = 0.093 hp/ft^2
1 W/m^2 = 5.7 10^{-3} psi in/s = 6.8 10^{-2} psf ft/s	1 hp/m^2 = 746 W/m^2 = 550 ft-lb/m^{2}s
1 W/m^2 = 0.23892 cal/m^{2}s	1 hp/m^2 = 51.097 psf•(ft/s)
1 W/m^2 = 10^7 erg/m^{2}s = 10^3 erg/cm^{2}s	1 psi•in/s = 175 W/m^2 = 1.75 10^8 μPa•(m/s)

B-15b. Intensity in Air and in Water

Unlike pressure, intensity depends on the acoustic impedance of the medium. Thus, for example, under the assumption of plane waves, the same pressure (first three columns) causes different intensities in water and in air (last two columns):

Pressure (rms)	SPL (dB re 1 μPa)	SPL (dB re 20 μPa)		Intensity in Water (W/m^2)	Intensity in Air (W/m^2)
0.017 μPa = (1/60) μPa	-35.6 dB	-61.6 dB		1.9 10^{-22} W/m^2	6.7 10^{-19} W/m^2
1 μPa = 10^{-5} dyn/cm^2	0 dB	-26 dB		6.7 10^{-19} W/m^2	2.4 10^{-15} W/m^2
20 μPa = 0.0002 μbar	26 dB	0 dB		2.7 10^{-16} W/m^2	9.6 10^{-13} W/m^2
1200 μPa = 60 (20 μPa)	61.6 dB	35.6 dB		9.6 10^{-13} W/m^2	3.4 10^{-9} W/m^2
1 μbar = 0.1 Pa = 10^5 μPa	100 dB	74 dB		6.7 10^{-9} W/m^2	2.4 10^{-5} W/m^2
2.04 10^7 μPa	146.2 dB	120.2 dB		2.8 10^{-4} W/m^2	1 W/m^2
1 psf = 4.8 10^7 μPa = 48 Pa	153.6 dB	127.6 dB		0.0015 W/m^2	5.5 W/m^2
1.2 10^9 μPa = 1.2 kPa	181.8 dB	155.8 dB		1 W/m^2	3600 W/m^2
1 psi = 6.9 10^9 μPa = 6.9 kPa	196.8 dB	170.8 dB		31.8 W/m^2	1.1 10^5 W/m^2
3.2 10^{10} μPa = 32 kPa = 66.7 psf	210 dB	184 dB		660.7 W/m^2	2.4 10^6 W/m^2
3.2 10^{12} μPa = 3200 kPa	250 dB	224 dB		6.6 10^6 W/m^2	2.4 10^{10} W/m^2

For a given pressure, the intensity in air is about 3600 times the intensity in water (because the impedance of water is about 3600 times the impedance of air). Hence the ratio of intensities in the last two columns is always about 3600. [Intensity for plane waves is proportional to time-averaged squared pressure divided by impedance.]

To achieve a given intensity in water requires about 60 times as much pressure as is required to achieve that same intensity in air (noting that 60^2 is 3600). Sample values in the table are selected to emphasize the factor of 60 in pressure, and to show the pressures required to yield a given intensity in air and in water (e.g., 20 μPa in air and 1200 μPa in water).

B-15c. Intensity Level

It is nearly universal practice to use SPL in place of intensity level. This makes sense as long as impedance is constant. In that case, intensity is proportional to short-term-average, squared pressure, with proportionality constant equal to the impedance.

When the impedance differs significantly in space or time (as in noise propagation from air into water), the intensity level must specify the value of the impedance in the reference.

B-15d. Intensity Levels in Air and in Water

Because plane-wave intensity is equivalent to the average squared pressure normalized by impedance, treatment of intensity in different media requires care. The table below is the decibel version of the table given in B-15b above. It shows the relationship of SPL to intensity in air and in water.

Sound Pressure Level (SPL)	Intensity Level In Water	Intensity Level In Air
X dB re 1 μPa	(X – 181.8) dB re 1 W/m^2	(X – 146.2) dB re 1 W/m^2
Y dB re 1 μbar = (Y + 100) dB re 1μPa	(Y – 81.8) dB re 1 W/m^2	(Y – 46.2) dB re 1 W/m^2
Z dB re 20 μPa = (Z – 74) dB re 1 μbar	(Z – 155.8) dB re 1 W/m^2	(Z – 120.2) dB re 1 W/m^2
(X + 61.8) dB re 1 μPa = (X + 35.8) dB re 20 μPa	(X – 120) dB re 1 W/m^2	(X – 84.4) dB re 1 W/m^2
(Y – 35.8) dB re 1 μPa	(Y – 217.6) dB re 1 W/m^2	(Y – 182.0) dB re 1 W/m^2
Z dB re 1 psi = (Z + 16.8) dB re 1 kPa = (Z + 196.8) dB re 1 μPa	(Z + 15) dB re 1 W/m^2	(Z + 50.6) dB re 1 W/m^2
X dB re 1 psf = (X – 43.2) dB re 1 psi = (X + 153.6) dB re 1 μPa	(X - 28.2) dB re 1 W/m^2	(X + 7.4) dB re 1 W/m^2
(Y – 15) dB re 1 psi = (Y + 1.8) dB re 1 kPa = (Y + 181.8) dB re 1 μbar = (Y + 155.8) dB re 20 μPa	Y dB re 1 W/m^2 = (Y – 40) dB re 1 W/cm^2 = (Y – 37) dB re 1 psi-in/s	(Y + 35.6) dB re 1 W/m^2
(Z – 7.4) dB re 1 psf = (Z – 50.6) dB re 1 psi = (Z + 146.2) dB re 1 μPa = (Z + 120.1) dB re 20 μPa	(Z – 35.6) dB re 1 W/m^2	Z dB re 1 W/m^2

B-16. ACOUSTIC ENERGY FLUX DENSITY

B-16a. ACOUSTIC ENERGY FLUX DENSITY

[Pressure^2 • Time]/Impedance = Intensity • Time = Energy/Area)	1 J/cm^2 = 10^4 J/m^2 = 10^7 erg/cm^2
1 W•s/m^2 = 1 J/m^2 = 1 N/m = 1 Pa•m	1 psi•in = 175 J/m^2 = 1.75 10^8 μPa•m
1 J/m^2 = 10^6 μPa•m	1 lb/ft = 14.596 J/m^2 = 14.596 W•s/m^2
1 J/m^2 = 10^7 erg/m^2 = 10^3 erg/cm^2 = 10^3 dyn/cm	1 hp•s/m^2 = 0.093 hp•s/ft^2
1 J/m^2 = 5.7 10^{-3} psi•in = 6.8 10^{-2} psf•ft	1 hp•s/m^2 = 746 J/m^2
1 J/m^2 = 0.23892 cal/m^2	1 hp•s/m^2 = 550 ft-lb/m^2 = 51.097 psf•ft

B-16b. Energy (Flux Density) Level (EFDL) Referred to Pressure^2 Time

Note that the abbreviation EFDL is not in general usage, but is used here for convenience. Just as the usual reference for intensity level is pressure^2 (and not intensity itself), the reference often (but not always) used for EFDL is *Pressure^2 • Time*. This makes sense when the impedance is constant. Some examples of conversions follow:

EFDL = X dB re 1 $\mu Pa^2 \cdot s$ = (X - 26) dB re $(20\ \mu Pa)^2 \cdot s$ = (X - 197) dB re 1 $psi^2 \cdot s$

EFDL = Y dB re 1 erg/cm^2 = (Y + 52) dB re 1 $(dyn/cm^2)^2 \cdot s$ = (Y + 152) dB re 1 $\mu Pa^2 \cdot s$

EFDL = Z dB re $(1\ dyn/cm^2)^2 \cdot s$ = (Z + 100) dB re 1 $\mu Pa^2 \cdot s$

B-16c. Energy (Flux Density) Level (EFDL) Referred to Energy Metrics

EFDL is often stated in reference to a nominal value in energy flux density units (such as J/m^2, erg/cm^2, psi•in). Such a practice is very rare for intensity. Nonetheless, the acoustics literature (especially the older literature) suggests that this reference may be used as often as the one given above (pressure$^2 \times$ time). The two references differ by a factor equal to the impedance, and hence require a specification of the medium. (Some examples using both references are given in B-16e and B-16f.)

EFDL = X dB re 1 J/m^2 = X dB re 1 Pa•m = X dB re 1 $W \cdot s/m^2$

= X dB re 1 N/m = (X + 60) dB re 1 μPa•m

= (X – 22.4) dB re 1 psi•in = (X – 11.7) dB re 1 psf•ft

= (X + 30) dB re 1 dyn/cm

B-16d. Note On Energy Flux Density

Energy Flux Density or EFD (as opposed to intensity or mean-square pressure) is the usual integrated metric for underwater impulsive signals. It is essentially the same as Sound Exposure Level (SEL) over exposure time equal to the full signal duration.

EFD is defined as the integral over time of the pressure times the particle velocity in the direction of propagation. For plane or spherical waves (the usual cases), the EFD can be calculated as the time integral of the squared pressure, normalized by the acoustic impedance (density times sound speed). EFD has units of *J/m^2*.

Whereas the acoustic intensity (like normalized mean square pressure) makes sense as a metric for continuous signals in which the mean square is not very sensitive to averaging time, the intensity of an impulsive signal will depend on both the beginning and end points of the integration time. The EFD, on the other hand, has no time averaging function and integrates over "all" time (i.e., the total time when the signal of interest is present). The EFD for a pure tone of infinite duration (with well-defined and constant intensity) does not exist (has arbitrarily large value).

B-16e. Energy Flux Density (EFD) Metrics in Air and in Water

[Pressure (rms)]^2 [Time]	EFD In Water	EFD In Air
1 $\mu Pa^2 \bullet s$	(6.7) 10^{-19} J/m^2	(2.4) 10^{-15}Jm^2
1 $\mu bar^2 \bullet s = [0.1\ Pa]^2 \bullet s$	(6.7) 10^{-9} J/m^2	(2.4) 10^{-5} J/m^2
$[20\ \mu Pa]^2 \bullet s = [0.0002\ \mu bar]^2 \bullet s$	(3) 10^{-16} J/m^2	(1.0) 10^{-12} J/m^2

B-16f. Energy Flux Density (EFD) Levels in Air and in Water

(Pressure^2 •Time) Level	EFD Level In Water	Level In Air
X dB re 1 $\mu Pa^2 \bullet s$	(X – 181.8) dB re 1 J/m^2	(X – 146.2) dB re 1 J/m^2
Y dB re 1 $\mu bar^2 \bullet s$ = (Y + 100) dB re 1 $\mu Pa^2 \bullet s$	(Y – 81.8) dB re 1 J/m^2	(Y – 46.2) dB re 1 J/m^2
Z dB re 20 $\mu Pa^2 \bullet s$ = (Z – 74) dB re 1 $\mu bar^2 \bullet s$	(Z – 155.8) dB re 1 J/m^2	(Z – 120.2) dB re 1 J/m^2
(X + 61.8) dB re 1 $\mu Pa^2 \bullet s$ = (X+ 35.8) dB re 20 $\mu Pa^2 \bullet s$	(X – 120) dB re 1 J/m^2	
(Y – 35.6) dB re 1 $\mu Pa^2 \bullet s$		(Y – 182.0) dB re 1 J/m^2
Z dB re 1 $psi^2 \bullet s$ = (Z + 16.8) dB re 1 $kPa^2 \bullet s$ = (Z + 196.8) dB re 1 $\mu Pa^2 \bullet s$	(Z + 15) dB re 1 J/m^2	(Z + 50.6) dB re 1 J/m^2
X dB re 1 $psf^2 \bullet s$ = (X + 43.2) dB re 1 $psi^2 \bullet s$ = (X + 153.6) dB re 1 $\mu Pa^2 \bullet s$	(X – 28.2) dB re 1 J/m^2	(X + 7.4) dB re 1 J/m^2

B-17. ACOUSTIC POWER SPECTRUM

INTENSITY/FREQUENCY	1 W/m^2 •Hz = 10^4 W/m^2 Hz = 10^7 erg/cm^2
1 W/m^2 •Hz = 1 J/(s•m^2 Hz) = 1 N/m•s Hz = 1 N/m	1 psi•in = 175 W/m^2 Hz = 1.75 10^8 μPa•(m/s)/Hz
1 W/m^2 •Hz = 1 Pa•(m/s Hz) = 10^6 μPa•m	1 lb/ft•s•Hz = 14.596 J/m^2 = 14.596 W/m^2 • Hz
1 W/m^2 •Hz = 10^3 dyn/cm	1 hp/m^2•Hz = 0.093 hp/ft^2 • Hz
1 W/m^2 •Hz = 5.7 10^{-3} psi•in = 6.8 10^{-2} psf•ft	1 hp/m^2•Hz = 746 W/m^2 • Hz = 550 ft-lb/m^2
1 W/m^2 •Hz = 10^7 erg/m^2 = 10^3 erg/cm^2	1 hp/m^2•Hz = 51.097 psf • ft
1 W/m^2 •Hz = 0.23892 cal/m^{2}s Hz = 0.23892 cal/m^2	

B-18 ACOUSTIC ENERGY SPECTRUM

To help visualize the frequency dependence of a transient signal, and to allow calculation of the band energy levels as thresholds, the energy spectrum is the natural choice. It is calculated as the fourier transform of the unaveraged auto-correlation function, normalized by the impedance. It can also be calculated directly as the squared modulus of the fourier transform of the pressure, but without time averaging and with normalization.

Whereas the intensity or power spectrum has units of (W/m^2)/Hz, the energy spectrum has units of (W•s/m^2)/Hz or (J/m^2)/Hz, sometimes written as W•s^2/m^2. In decibels, the usual approach is analogous to that for intensity, the reference quantity is usually the non-normalized product of squared pressure and time, per band. The usual expression is

$$\text{dB re } 1\ \mu Pa^2 \bullet s/Hz.$$

B-19. SUMMARY OF AIR/WATER RELATIONSHIPS

Typical Values of Medium Properties

Property	Water	Air (20°C, sea level)	Ratio (water/air)
Density	1000 kg/m^3	1.225 kg/m^3	816.3
Sound Speed	1500 m/s	344 m/s	4.36
Impedance	1.5×10^6 $kg/m^2 \bullet s$	421.4 $kg/m^2 \bullet s$	3559.6
Static Pressure	(1 + 0.1 Depth (m)) atm.	1 atm.	1 + 0.1 Depth (m)

In general,

intensity = (pressure) × (particle velocity in direction of propagation)

or

$$I=pv.$$

For plane waves, the role of the large impedance difference between air and water is clear:

pressure = impedance × particle velocity $[\ p = (\rho c)v\ ]$

intensity = impedance × (particle velocity)^2 $[\ I = (\rho c)v^2\ ]$

= pressure^2 / impedance $[\ I = p^2/\rho c\ ]$

particle velocity = pressure/impedance $[\ v = p/\rho c\ ]$

Intensity in Air and in Water for Given Pressure Level

For plane-wave pressure p in air, the corresponding intensity is in air is

$$I_a = p^2/(\rho c)_a .$$

For the same value of pressure p in water, the intensity is much less:

$$I_w = p^2/(\rho c)_w << I_a,$$

since

$$(\rho c)_w >> (\rho c)_a.$$

In fact,

$$I_a/I_w = (\rho c)_w / (\rho c)_a \approx 3600.$$

For the same pressure levels, intensity in air is about 3600 times greater than that in water.

Likewise for the particle velocities:

$$v_a/v_w = (\rho c)_w / (\rho c)_a \approx 3600.$$

For example, if the rms pressure in air is 1.2 10^9 μPa (an SPL of about 181 dB re 1μPa), then the corresponding plane-wave intensity in air is about 3600 W/m^2 . If the rms pressure in water is also 1.2 10^9 μPa, then the intensity in water is only about 1 W/m^2.

On the other hand, the pressure in water corresponding to an intensity in water of 3600 W/m^2 is about 7.2 10^{10} μPa (or about 217 dB re 1μPa). This is about 60 times the pressure in air (about 36 dB greater SPL) that results in an intensity in air of 3600 W/m^2.

See the tables in subsections B-15.b and B-15.d for more examples.

The tables below show pressure levels and intensities for some typical sound conditions.

Sound in Water	**SPL in Water (dB re 1μPa)**	**SPL in Water (dB re 20 μPa)**	**Intensity in Water (W/m^2)**
Ambient Noise Spectrum Level at 20 kHz (light winds)	40	14	6.6 10^{-15}
Hearing Threshold for Dolphin at 20 kHz	40	14	6.6 10^{-15}
Hearing Threshold for Human at 1000 Hz	66	40	2.6 10^{-12}
Ambient Noise Spectrum Level at 50 Hz (typical open ocean)	85	59	2 10^{-10}
Range of Harassment Thresholds for Baleen Whales (1 sec. tone at 50 Hz)	120 – 180	94-154	6.6 10^{-7} to 0.7
Range of Harassment Thresholds for Dolphins (1 second tone at 20 kHz)	120 –192	94-166	6.6 10^{-7} to 10
Merchant Ship Source Spectrum Level at 50 Hz (re 1 m)	140 - 190	114 - 164	6.6 10^{-5} to 6.6
Hearing Threshold for Dolphin at 100 Hz	140	114	6.6 10^{-5}
ATOC Source Level at 1 m	195	169	20
Source Level for Fish-Finder at 1 m	225	199	1000
High-Power-Sonar Source Level at 1 m	240	214	6.6 10^{5}

Sound in Air	**SPL in Air (dB re 1μPa)**	**SPL in Air (dB re 20 μPa)**	**Intensity in Air (W/m^2)**
Threshold of Human Hearing at 1 kHz	26	0	$9.6\ 10^{-13}$
Very Quiet Living Room	66	40	$9.6\ 10^{-9}$
Normal Speech	86	60	$9.6\ 10^{-7}$
Jet Airliner at 10 m	130	104	0.02
Threshold of Human Feeling at 1 kHz	146	120	1.0
Jet Airliner Source Level (re 1 m)	150	124	2.4
Human Threshold of Pain	166	140	95
Intense (10 psf) Sonic Boom	174	148	600

APPENDIX C. TYPICAL VALUES OF SELECTED VARIABLES AND CONSTANTS

Acceleration Of Gravity
$g = 9.807 \text{ m/s}^2 = 32.174 \text{ ft/s}^2$

Density Of Water (ρ_w)

At 4° C, $\rho_w \approx 1000 \text{ kg/m}^3 = 1 \text{ g/cm}^3$

Density of seawater is nearly independent of temperature and depth.

Density Of Air (ρ_a)
Typical densities taken from the Smithsonian Tables are:

ALTITUDE (km)	DENSITY (kg/m^3)	ALTITUDE (km)	DENSITY (kg/m^3)
0	1.22	20	.09
2	1.00	40	$3.5\ 10^{-3}$
5	0.74	60	$3.5\ 10^{-4}$
10	0.41	80	$4.6\ 10^{-5}$
15	0.19	120	$4.4\ 10^{-7}$

Speed Of Sound In Air (c_a)

At 0 Degrees C, One Atmosphere, 0.03% CO_2 : 331.45 m/s
At 60 Degrees C: 366.05 m/s
At –90 Degrees C: 271.4 m/s
Change in Sound Speed/Change in Temperature ≈ (0.6 m/s) per degree
For warm, humid air, near the ground, add up to 5 m/s.

Speed Of Sound In Water (c_w)

The speed of sound in water varies no more than 3% over geographic area, depth and season. For rough estimates of impedance and travel time, nominal values of 1500 m/s and 5000 ft/s are often used.

Hydrostatic Pressure (Of Water On Earth):

Hydrostatic Pressure in Atmospheres ≈ 1 + (0.1)Depth (m)

Hence, static pressure in water increases by one atmosphere (14.5 psi or 101 kPa) for each 10 m of water.

Atmospheric Pressure

Standard pressure at sea level (NACA): 760 mm Hg = 29.921 in Hg ≈ 1014 mbar
= 101.3 kPa = 14.85 psi

Atmospheric Temperature

Standard (NACA) time lapse is: $a = 0.0065°$ C per meter (or 0.00357° F per foot)

$T = T_0 - aZ$ where Z is altitude in meters.

Standard (NACA) temperature at sea level: 15° C = 59° F

Standard isothermal layer temperature: -55° C = -67° F.

"Standard" Atmospheres

NACA STANDARD ATMOSPHERE, LOWER ATMOSPHERE

ALTITUDE (m)	TEMPERATURE (°C)	SOUND SPEED (m/s)	PRESSURE (mbar)
0	15.0	340	1013
500	11.8	338	955
1000	8.5	336	899
2000	2.0	332	795
3000	- 4.5	328	701
5000	-17.5	321	540
8000	- 37.0	309	356
10000	- 50.0	301	264
10769	- 55.0	298	235
15000	- 55.0	298	121
20000	- 55.0	298	55

NACA STANDARD ATMOSPHERE, UPPER ATMOSPHERE (DAYTIME)

ALTITUDE (m)	TEMPERATURE (°C)	SOUND SPEED (m/s)	PRESSURE (mbar)
20,000	-55	296	55
30,000	-55	296	11.5
40,000	04	334	2.8
60,000	77	375	0.35
80,000	-33	311	0.03
100,000	29	392	0.003
120,000	102	436	0.0006

APPENDIX D. CONVERSION TABLES

Conversion of units for quantities used in acoustics is often tedious and sometimes complicated. The conversion tables given below are printouts from spread sheets, which spread sheets the reader can easily reproduce from any row of the tables.

For each of several important quantities, tables show the most popular units and indicate equivalent values in each row. SI-based or SI-derived units are included in each table.

Tables and quantities are listed below:

TABLE	QUANTITY
D-1	TIME
D-2	LENGTH
D-3	VELOCITY (SPEED)
D-4	AREA
D-5	VOLUME
D-6	MASS
D-7	DENSITY
D-8	FORCE
D-9	ENERGY
D-10	POWER
D-11	PRESSURE

TABLE	QUANTITY
C-12	ACOUSTIC IMPULSE
D-13	ACOUSTIC IMPEDANCE
D-14	ACOUSTIC INTENSITY IN AIR
D-15	ACOUSTIC INTENSITY IN WATER
D-16	ACOUSTIC ENERGY FLUX DENSITY
D-17	SOUND PRESSURE LEVEL
D-18	SPL EXAMPLES
D-19	EXAMPLES FOR PSF AND PSI
D-20	SPL, INTENSITY (AIR), LEVELS
D-21	SPL, INTENSITY (WATER), LEVELS
D-22	EXAMPLES FOR PRESSURE AND INTENSITY IN AIR AND IN WATER

TABLE D-1. TIME

μs	ms	s	min	hr	day	nominal month	year
3.156E+13	3.156E+10	3.156E+07	5.26E+05	8766.	365.25	12.	1
2.63E+12	2.63E+09	2.63E+06	4.383E+04	730.5	30.4375	1	0.0833
8.64E+10	8.64E+07	8.64E+04	1440.	24.	1	0.0329	0.0027
3.6E+09	3.6E+06	3600.	60.	1	0.0417	0.0014	1.141E-04
6.0E+07	6.0E+04	60.	1	0.0167	6.944E-04	2.282E-05	1.901E-06
1.0E+06	1000.	1	0.0167	2.778E-04	1.157E-05	3.803E-07	3.169E-08
1000.	1	1.0E-03	1.667E-05	2.778E-07	1.157E-08	3.803E-10	3.169E-11
1	0.001	1.0E-06	1.667E-08	2.778E-10	1.157E-11	3.803E-13	3.169E-14

TABLE D-2. LENGTH

angstrom	mm	cm	inch (in)	foot (ft)	yards (yd)	meters (m)	fathoms (f)	kyd	km	statute mi	nmi
1.	1.0E-07	1.0E-08	3.937E-09	3.281E-10	1.094E-10	1.0E-10	5.468E-11	1.094E-13	1.0E-13	6.214E-14	5.396E-14
1.0E+07	1.	0.1	0.0394	0.0033	0.0011	0.001	5.468E-04	1.094E-06	1.0E-06	6.214E-07	5.396E-07
1.0E+08	10.	1.	0.3937	0.0328	0.0109	0.01	0.0055	1.094E-05	1.0E-05	6.214E-06	5.396E-06
2.54E+08	25.4	2.54	1.	0.0833	0.0278	0.0254	0.0139	2.778E-05	2.54E-05	1.578E-05	1.371E-05
3.048E+09	304.8	30.48	12.	1.	0.3333	0.3048	0.1667	3.333E-04	3.048E-04	1.894E-04	1.645E-04
9.144E+09	914.4	91.44	36.	3.	1.	0.9144	0.5	0.001	9.144E-04	5.682E-04	4.934E-04
1.0E+10	1000.	100.	39.3701	3.2808	1.0936	1.	0.5468	0.0011	0.001	6.214E-04	5.396E-04
1.829E+10	1828.8	182.88	72.	6.	2.	1.8288	1.	0.002	0.0018	0.0011	9.868E-04
9.144E+12	9.144E+05	9.144E+04	3.6E+04	3000.	1000.	914.4	500.	1.	0.9144	0.5682	0.4934
1.0E+13	1.0E+06	1.0E+05	3.937E+04	3280.8399	1093.6133	1000.	546.8066	1.0936	1.	0.6214	0.5396
1.609E+13	1.609E+06	1.609E+05	6.336E+04	5280.	1760.	1609.344	880.	1.76	1.6093	1.	0.8684
1.853E+13	1.853E+06	1.853E+05	7.296E+04	6080.2	2026.7333	1853.245	1013.3667	2.0267	1.8532	1.1516	1.

TABLE D-3. VELOCITY (SPEED)

SPEED = LENGTH/TIME

cm/s	ft/s	m/s	ft/min	km/hr	mile/hr (mph)	nmi/hr (knot)	km/min	miles/s	km/s
1.	0.0328	0.01	1.9685	0.036	0.0224	0.0194	6.0E-04	6.214E-06	1.0E-05
30.4804	1.	0.3048	60.0006	1.0973	0.6823	0.5925	0.0183	1.894E-04	3.048E-04
100.	3.2808	1.	196.85	3.6	2.2383	1.9438	0.06	6.214E-04	0.001
0.508	0.0167	0.0051	1.	0.0183	0.0114	0.0099	3.048E-04	3.157E-06	5.08E-06
27.7778	0.9113	0.2778	54.6806	1.	0.6218	0.54	0.0167	1.726E-04	2.778E-04
44.676	1.4657	0.4468	87.9448	1.6083	1.	0.8684	0.0268	2.776E-04	4.468E-04
51.4445	1.6878	0.5144	101.2684	1.852	1.1515	1.	0.0309	3.197E-04	5.144E-04
1666.6667	54.68	16.6667	3280.8333	60.	37.3056	32.3974	1.	0.0104	0.0167
1.609E+05	5280.	1609.3636	3.168E+05	5793.7089	3602.297	3128.3517	96.5618	1.	1.6094
1.0E+05	3280.8	1000.	1.969E+05	3600.	2238.3364	1943.844	60.	0.6214	1.

TABLE D-4. AREA

cm^2	in^2	m^2	ft^2	yd^2	$mile^2$	nmi^2	acre	km^2
1.	0.155	1.0E-04	0.0011	1.196E-04	3.861E-11	2.911E-11	2.471E-08	1.0E-10
6.4516	1.	6.452E-04	0.0069	7.716E-04	2.491E-10	1.878E-10	1.594E-07	6.452E-10
10000.	1550.0031	1.	10.7639	1.196	3.861E-07	2.911E-07	2.471E-04	1.0E-06
929.0304	144.	0.0929	1.	0.1111	3.587E-08	2.704E-08	2.296E-05	9.29E-08
8361.2736	1296.	0.8361	9.	1.	3.228E-07	2.434E-07	2.066E-04	8.361E-07
2.59E+10	4.015E+09	2.59E+06	2.788E+07	3.098E+06	1.	0.754	640.0805	2.5903
3.436E+10	5.325E+09	3.436E+06	3.698E+07	4.109E+06	1.3263	1.	848.9677	3.4357
4.047E+07	6.273E+06	4046.8564	4.356E+04	4840.	0.0016	0.0012	1.	0.004
1.0E+10	1.55E+09	1.0E+06	1.076E+07	1.196E+06	0.3861	0.2911	247.1054	1.

TABLE D-5. VOLUME

cm^3	in^3	ft^3	yd^3	m^3	quart	gallon	liter (l)
1.	0.061	3.531E-05	1.308E-06	1.0E-06	0.0011	2.642E-04	0.001
16.3871	1.	5.787E-04	2.143E-05	1.639E-05	0.0173	0.0043	0.0164
2.832E+04	1727.9986	1.	0.037	0.0283	29.9221	7.4805	28.3168
7.646E+05	4.666E+04	27.	1.	0.7646	807.8959	201.974	764.5548
1.0E+06	6.102E+04	35.3147	1.308	1.	1056.688	264.172	1000.
946.3531	57.75	0.0334	0.0012	9.464E-04	1.	0.25	0.9464
3785.4125	230.9999	0.1337	0.005	0.0038	4.	1.	3.7854
1000.	61.0237	0.0353	0.0013	0.001	1.0567	0.2642	1.

TABLE D-6. MASS

grain (gr.)	gram (g.)	oz.(avoir.*)	lb (avoir.*)	kg	metric T.	ton (T.)
3.969E+08	9.072E+05	3.2E+04	2000.0027	907.1858	0.9072	1.
4.375E+08	1.0E+06	3.527E+04	2204.623	1000.	1.	1.1023
4.375E+05	999.9994	35.274	2.2046	1.	0.001	0.0011
1.984E+05	453.592	16.	1.	0.4536	4.536E-04	5.0E-04
1.24E+04	28.3495	1.	0.0625	0.0283	2.835E-05	3.125E-05
437.5	1.	0.0353	0.0022	0.001	1.0E-06	1.102E-06
1.	0.0023	8.063E-05	5.039E-06	2.286E-06	2.286E-09	2.52E-09

*avoirdupois

TABLE D-7. DENSITY

DENSITY = MASS/VOLUME

g/cm^3	g/l.	kg/m^3	oz/in^3	lb/in^3	lb/ft^3	lb/gal
1.	1000.	1000.	0.578	0.0361	62.4292	8.3456
0.001	1.	1.	5.78E-04	3.613E-05	0.0624	0.0083
1.73	1729.9601	1729.9601	1.	0.0625	108.	14.4375
27.6794	2.768E+04	2.768E+04	16.	1.	1728.	231.
0.016	16.0181	16.0181	0.0093	5.787E-04	1.	0.1337
0.1198	119.8241	119.8241	0.0693	0.0043	7.4805	1.

TABLE D-8. FORCE

FORCE = MASS x ACCELERATION

lb (weight)	$kg(m/s^2)$	N (newton)	kg (weight)	erg/cm	dyne(dyn)	$g\ cm/s^2$	gram (weight)
1.	4.4482	19.7867	0.4536	4.448E+05	1.979E+06	4.448E+05	453.6
0.2248	1.	4.4482	0.102	1.0E+05	4.448E+05	1.0E+05	101.9734
2.2046	9.8065	43.6214	1.	9.806E+05	4.362E+06	9.806E+05	1000.
2.248E-06	1.0E-05	4.448E-05	1.02E-06	1.	4.4482	1.	0.001
0.0022	0.0098	0.0436	0.001	980.6481	4362.1387	980.6481	1.

TABLE D-9. ENERGY

ENERGY = WORK = FORCE x DISTANCE

$(g\text{-}cm^2)/s^2$ = dyn-cm = erg	in-lb	N-m = Joule = $(kg\text{-}m^2)/s^2$	ft-lb	kg-m	Btu	hp-hr	kW-hr	liter-atm
1.	6.146E-09	1.0E-07	7.376E-08	5.336E-07	9.478E-11	3.725E-14	2.778E-14	9.869E-10
1.627E+08	1.	16.2705	12.0005	86.8151	0.0154	6.061E-06	4.52E-06	0.1606
1.0E+07	0.0615	1.	0.7376	5.3357	9.478E-04	3.725E-07	2.778E-07	0.0099
1.356E+07	0.0833	1.3558	1.	7.2343	0.0013	5.051E-07	3.766E-07	0.0134
1.874E+06	0.0115	0.1874	0.1382	1.	1.776E-04	6.981E-08	5.206E-08	0.0018
1.055E+10	64.8432	1055.0292	778.1496	5629.3674	1.	3.93E-04	2.931E-04	10.4116
2.685E+13	1.65E+05	2.685E+06	1.98E+06	1.432E+07	2544.5005	1.	0.7457	2.649E+04
3.6E+13	2.213E+05	3.6E+06	2.655E+06	1.921E+07	3412.2289	1.341	1.	3.553E+04
1.013E+09	6.228	101.3317	74.7384	540.6801	0.096	3.775E-05	2.815E-05	1.

TABLE D-10. POWER

POWER = ENERGY/TIME = FORCE x VELOCITY

watt = joule/s	N m/s = $kg\text{-}m^2/s^2$	dyn-cm/s = erg/s	ft-lb/s	Btu/min	cal/min	cal/s	hp
1.	1.	1.0E+07	0.7376	0.0569	14.3307	0.2388	0.0013
1.0E-07	1.0E-07	1.	7.376E-08	5.687E-09	1.433E-06	2.388E-08	1.341E-10
1.3558	1.3558	1.356E+07	1.	0.0771	19.4298	0.3238	0.0018
17.5838	17.5838	1.758E+08	12.9692	1.	251.9882	4.1998	0.0236
0.0698	0.0698	6.978E+05	0.0515	0.004	1.	0.0167	9.358E-05
4.1868	4.1868	4.187E+07	3.088	0.2381	60.	1.	0.0056
745.6999	745.6999	7.457E+09	550.	42.4083	1.069E+04	178.1065	1.

TABLE D-11. PRESSURE

PRESSURE = FORCE/AREA

Pa = N/m^2	20 μPa =0.0002 μbar	μPa	dyn/cm^2 = μbar	psi	kg/cm^2	psf	atm	bar	kg/m^2	inches Hg	mm Hg
1.	5.0E+04	1.0E+06	10.	1.45E-04	1.02E-05	0.0209	9.869E-06	1.0E-05	0.102	2.953E-04	0.0075
2.0E-05	1.	20.	2.0E-04	2.901E-09	2.039E-10	4.177E-07	1.974E-10	2.0E-10	2.039E-06	5.906E-09	1.5E-07
1.0E-06	0.05	1.	1.0E-05	1.45E-10	1.02E-11	2.089E-08	9.869E-12	1.0E-11	1.02E-07	2.953E-10	7.501E-09
0.1	5000.	1.0E+05	1.	1.45E-05	1.02E-06	0.0021	9.869E-07	1.0E-06	0.0102	2.953E-05	7.501E-04
6894.7591	3.447E+08	6.895E+09	6.895E+04	1.	0.0703	144.	0.068	0.0689	703.0717	2.036	51.7176
9.807E+04	4.903E+09	9.807E+10	9.807E+05	14.2233	1.	2048.1552	0.9678	0.9807	10000.	28.9589	735.5949
47.8803	2.394E+06	4.788E+07	478.8027	0.0069	4.882E-04	1.	4.725E-04	4.788E-04	4.8824	0.0141	0.3591
1.013E+05	5.066E+09	1.013E+11	1.013E+06	14.6959	1.0332	2116.216	1.	1.0132	1.033E+04	29.9213	760.0389
1.0E+05	5.0E+09	1.0E+11	1.0E+06	14.5038	1.0197	2088.5429	0.9869	1.	1.02E+04	29.53	750.1001
9.8066	4.903E+05	9.807E+06	98.0662	0.0014	1.0E-04	0.2048	9.678E-05	9.807E-05	1.	0.0029	0.0736
3386.388	1.693E+08	3.386E+09	3.386E+04	0.4912	0.0345	70.7262	0.0334	0.0339	345.3164	1.	25.4013
133.3155	6.666E+06	1.333E+08	1333.1554	0.0193	0.0014	2.7844	0.0013	0.0013	13.5944	0.0394	1.

TABLE D-12. ACOUSTIC IMPULSE

ACOUSTIC IMPULSE = INTEGRAL OF ACOUSTIC PRESSURE VERSUS TIME

psi μs	psi ms	psi s	psf ms	psf s	μPa ms	μPa s	Pa s	kPa s
1.	0.001	1.0E-06	6.944E-06	6.944E-09	6.895E+06	6895.	0.0069	6.895E-06
1000.	1.	0.001	0.0069	6.944E-06	6.895E+09	6.895E+06	6.895	0.0069
1.0E+06	1000.	1.	6.9444	0.0069	6.895E+12	6.895E+09	6895.	6.895
1.44E+05	144.	0.144	1.	0.001	9.929E+11	9.929E+08	992.88	0.9929
1.44E+08	1.44E+05	144.	1000.	1.	9.929E+14	9.929E+11	9.929E+05	992.88
1.45E-07	1.45E-10	1.45E-13	1.007E-12	1.007E-15	1.	1.0E-03	1.0E-09	1.0E-12
1.45E-04	1.45E-07	1.45E-10	1.007E-09	1.007E-12	1000.	1.	1.0E-06	1.0E-09
145.0326	0.145	1.45E-04	0.001	1.007E-06	1.0E+09	1.0E+06	1.	0.001
1.45E+05	145.0326	0.145	1.0072	0.001	1.0E+12	1.0E+09	1000.	1.

TABLE D-13. ACOUSTIC IMPEDANCE

ACOUSTIC IMPEDANCE = DENSITY X SOUND SPEED = PRESSURE/SPEED

	DENSITY OF MEDIUM		SOUND SPEED OF MEDIUM		IMPEDANCE					
	kg/m^3	lb/ft^3	m/s	ft/s	rayl (mks) = kg/s m^2	dyn s/cm^3 = g/s cm^2	(slug/ft^3)(ft/s)	lb s/ft^3	Pa (s/m)	μPa(s/m)
WATER	1000.	62.43	1500.	4921.26	1.5E+06	1.5E+05	9545.44	3.072E+05	1.5E+06	1.5E+12
AIR	1.225	0.0765	344.	1128.609	421.4	42.14	2.6816	86.3124	421.4	4.214E+08
WATER/AIR	816.33	816.33	4.36	4.36	3559.56	3559.56	3559.57	3559.56	3559.56	3559.56
OTHER	1.	0.0624	1.	3.2808	1.	0.1	0.0064	0.2048	1.	1.0E+06
CASES	0.0624	1.	0.3048	1.	10.	1.	0.0636	2.0475	10.	1.0E+07
					157.1438	15.7144	1.	32.1752	157.1438	1.571E+08
					4.884	0.4884	0.0311	1.	4.884	4.884E+06
					1.	0.1	0.0064	0.2048	1.	1.0E+06
					1.0E-06	1.0E-07	6.364E-09	2.048E-07	1.0E-06	1.

TABLE D-14. ACOUSTIC INTENSITY – IN AIR

INTENSITY = POWER/AREA = ENERGY/AREA x TIME = PRESSURE x SPEED

PLANE-WAVE ACOUSTIC INTENSITY = ($PRESSURE^2$)/IMPEDANCE

PLANE-WAVE PRESSURE			INTENSITY IN AIR						
μPa	psi	dB re 20 μPa	W/cm^2	Pa(m/s) =N/(m s)	W/m^2 =J/(s m^2)	cal./s-m^2	erg/s-m^2	(psf)(ft/s)	(psi)(in/s)
1.	1.449E-10	-26.0	2.3E-19	2.3E-15	2.3E-15	5.495E-16	2.3E-08	1.564E-16	1.311E-17
20.	2.899E-09	**0.0**	9.2E-17	9.2E-13	9.2E-13	2.198E-13	9.2E-06	6.256E-14	5.244E-15
6.90E+09	**1.**	170.8	10.9503	1.095E+05	1.095E+05	2.616E+04	1.095E+12	7446.204	624.1671
2.09E+09	0.3022	160.4	**1.**	10000.	10000.	2389.	1.0E+11	680.	57.
2.09E+07	0.003	120.4	1.0E-04	**1.**	**1.**	0.2389	1.0E+07	0.068	0.0057
4.27E+07	0.0062	126.6	4.186E-04	4.1859	4.1859	**1.**	4.186E+07	0.2846	0.0239
6.59E+03	9.556E-07	50.4	1.0E-11	1.0E-07	1.0E-07	2.389E-08	**1.**	6.8E-09	5.7E-10
8.00E+07	0.0116	132.0	0.0015	14.7059	14.7059	3.5132	1.471E+08	**1.**	0.0838
2.76E+08	0.04	142.8	0.0175	175.4386	175.4386	41.9123	1.754E+09	11.9298	**1.**

TABLE D-15. ACOUSTIC INTENSITY -- IN WATER

INTENSITY = POWER/AREA = ENERGY/AREA x TIME = PRESSURE x SPEED

PLANE-WAVE ACOUSTIC INTENSITY = (PRESSURE^2)/IMPEDANCE

PLANE-WAVE PRESSURE			INTENSITY IN WATER						
μPa	psi	dB re 20 μPa	W/cm^2	Pa(m/s) =N/(m s)	W/m^2 =J/(s m^2)	cal./s-m^2	erg/s-m^2	(psf)(ft/s)	(psi)(in/s)
1.	1.449E-10	-26.0	6.7E-23	6.7E-19	6.7E-19	1.601E-19	6.7E-12	4.56E-20	3.82E-21
20.	2.899E-09	**0.0**	2.68E-20	2.68E-16	2.68E-16	6.40E-17	2.68E-09	1.82E-17	1.53E-18
6.90E+09	**1.**	170.8	0.0032	31.8987	31.8987	7.6206	3.19E+08	2.1691	0.1818
1.22E+11	17.7057	195.7	**1.**	10000.	10000.	2389.	1.0E+11	680.	57.
1.22E+09	0.1771	155.7	1.0E-04	1.	1.	0.2389	1.0E+07	0.068	0.0057
2.50E+09	0.3622	161.9	4.19E-04	4.1859	4.1859	**1.**	4.19E+07	0.2846	0.0239
3.86E+05	5.60E-05	85.7	1.0E-11	1.0E-07	1.0E-07	2.39E-08	**1.**	6.8E-09	5.7E-10
4.68E+09	0.679	167.4	0.0015	14.7059	14.7059	3.5132	1.471E+08	**1.**	0.0838
1.62E+10	2.3452	178.2	0.0175	175.4386	175.4386	41.9123	1.754E+09	11.9298	**1.**

TABLE D-16. ENERGY FLUX DENSITY

EFD = INTENSITY x TIME = (PRESSURE^2 x TIME)/IMPEDANCE

W s/m^2 = N/m = J/m^2 = Pa m	in-lb/in^2 = lb/in = psi in	ft-lb/ft^2 = lb/ft = psf ft	erg/m^2	dyn/cm = erg/cm^2	μPa m	hp s/ft^2	cal/m^2	ft-lb/m^2	W s/cm^2
1.	0.0057	0.068	1.0E+07	1000.	1.0E+06	1.25E-04	0.2389	0.7343	1.0E-04
175.4386	1.	11.9298	1.75E+09	1.75E+05	1.75E+08	0.0219	41.9123	128.8246	0.0175
14.7059	0.0838	1.	1.47E+08	1.47E+04	1.47E+07	0.0018	3.5132	10.7985	0.0015
1.0E-07	5.7E-10	6.8E-09	1.	1.0E-04	0.1	1.25E-11	2.39E-08	7.34E-08	1.0E-11
0.001	5.7E-06	6.8E-05	10000.	1.	1000.	1.25E-07	2.39E-04	7.34E-04	1.0E-07
1.0E-06	5.7E-09	6.8E-08	10.	0.001	1.	1.25E-10	2.39E-07	7.34E-07	1.0E-10
8019.2462	45.7097	545.3087	8.02E+10	8.02E+06	8.02E+09	1.	1915.7979	5888.5325	0.8019
4.1859	0.0239	0.2846	4.19E+07	4185.8518	4.19E+06	5.22E-04	1.	3.0737	4.19E-04
1.3618	0.0078	0.0926	1.36E+07	1361.8412	1.36E+06	1.698E-04	0.3253	1.	1.36E-04
10000.	57.	680.	1.0E+11	1.0E+07	1.0E+10	1.247	2389.	7343.	1.

TABLE D-17. SOUND PRESSURE LEVEL (SPL)

PRESSURE				SPL								
μPa	kPa	psi	psf	dB re 1 μPa	dB re 20 μPa	dB re 0.0002 μbar	dB re 1 dyn/cm^2	dB re 1 μbar	dB re 1 psi	dB re 1 psf	dB re 1 Pa	dB re 1 kPa
1.	1.0E-09	1.45E-10	2.089E-08	0.0	-26.0	-26.0	-100.0	-100.0	-196.8	-153.6	-120.0	-180.0
20.	2.0E-08	2.901E-09	4.177E-07	26.0	0.0	0.0	-74.0	-74.0	-170.8	-127.6	-94.0	-154.0
1.0E+05	1.0E-04	1.45E-05	0.0021	100.0	74.0	74.0	0.0	0.0	-96.8	-53.6	-20.0	-80.0
1.0E+06	0.001	1.45E-04	0.0209	120.0	94.0	0.0	20.0	20.0	-76.8	-33.6	0.0	-60.0
4.788E+07	0.0479	0.0069	1.	153.6	127.6	127.6	0.0	0.0	-43.2	0.0	33.6	-26.4
1.0E+09	1.	0.145	20.8858	180.0	154.0	154.0	80.0	80.0	-16.8	26.4	60.0	0.0
6.895E+09	6.8946	1.	144.	196.8	170.7	170.7	96.8	96.8	0.0	43.2	76.8	16.8
1.0E+11	100.	14.504	2088.576	220.0	194.0	194.0	120.0	120.0	23.2	66.4	0.0	

TABLE D-18. SPL EXAMPLES

PRESSURE				SPL						
μPa	psi	psf	kPa	dB re 1 μPa	dB re 20 μPa*	dB re 1 μbar**	dB re 1 psi	dB re 1 psf	dB re 1 Pa	dB re 1 kPa
1.	1.45E-10	2.088E-08	1.0E-09	0.0	-26.0	-100.0	-196.8	-153.6	-120.0	-180.0
6.90E+09	1.	144.	6.8966	196.8	170.8	96.8	0.0	43.2	76.8	16.8
4.79E+07	0.0069	1.	0.0479	153.6	127.6	53.6	-43.2	0.0	33.6	-26.4
1.0E+09	0.145	20.88	1.	180.0	154.0	80.0	-16.8	26.4	60.0	0.0
20.	2.9E-09	4.18E-07	2.0E-08	26.0	0.0	-74.0	-170.8	-127.6	-94.0	-154.0
4.79E+00	6.94E-10	1.0E-07	4.789E-09	13.6	-12.4	-86.4	-183.2	-140.0	-106.4	-166.4
2.39E+01	3.472E-09	5.0E-07	2.395E-08	27.6	1.6	-72.4	-169.2	-126.0	-92.4	-152.4
1.20E+02	1.736E-08	2.5E-06	1.197E-07	41.6	15.5	-58.4	-155.2	-112.0	-78.4	-138.4
5.99E+02	8.68E-08	1.25E-05	5.986E-07	55.5	29.5	-44.5	-141.2	-98.1	-64.5	-124.5
2.99E+03	0.000	6.25E-05	2.993E-06	69.5	43.5	-30.5	-127.2	-84.1	-50.5	-110.5
1.50E+04	0.000	3.125E-04	1.497E-05	83.5	57.5	-16.5	-113.3	-70.1	-36.5	-96.5
7.48E+04	0.000	0.0016	7.483E-05	97.5	71.5	-2.5	-99.3	-56.1	-22.5	-82.5
3.74E+05	0.000	0.0078	3.741E-04	111.5	85.4	11.5	-85.3	-42.1	-8.5	-68.5
1.87E+06	0.00	0.0391	0.0019	125.4	99.4	25.4	-71.3	-28.2	5.4	-54.6
9.35E+06	0.00	0.1953	0.0094	139.4	113.4	39.4	-57.4	-14.2	19.4	-40.6
4.68E+07	0.01	1.0	0.0468	153.4	127.4	53.4	-43.4	-0.2	33.4	-26.6
2.34E+08	0.03	4.9	0.2338	167.4	141.4	67.4	-29.4	13.8	47.4	-12.6
1.17E+09	0.2	24.4	1.1692	181.4	155.3	81.4	-15.4	27.7	61.4	1.4
5.85E+09	0.8	122.1	5.8461	195.3	169.3	95.3	-1.4	41.7	75.3	15.3
2.92E+10	4.2	610.3	29.2303	209.3	183.3	109.3	12.5	55.7	89.3	29.3
1.46E+11	21.2	3051.6	146.1517	223.3	197.3	123.3	26.5	69.7	103.3	43.3
7.31E+11	106.0	1.53E+04	730.76	237.3	211.3	137.3	40.5	83.7	117.3	57.3
3.65E+12	529.8	7.63E+04	3.65E+03	251.3	225.2	151.3	54.5	97.6	131.3	71.3
1.83E+13	2649.0	3.81E+05	1.83E+04	265.2	239.2	165.2	68.5	111.6	145.2	85.2
9.13E+13	13245.0	1.91E+06	9.13E+04	279.2	253.2	179.2	82.4	125.6	159.2	99.2
4.57E+14	66225.0	9.54E+06	4.57E+05	293.2	267.2	193.2	96.4	139.6	173.2	113.2
2.28E+15	331125.0	4.77E+07	2.28E+06	307.2	281.2	207.2	110.4	153.6	187.2	127.2

* or dB re 0.0002 μbar

** or dB re 1 dyn/cm^2

TABLE D-19
EXAMPLES FOR UNITS BASED ON PSI AND PSF

PRESSURE lb/ft^2	PRESSURE lb/in^2	PRESSURE mPa	PRESSURE kPa	SPL dB re 1 mPa	SPL dB re 20 mPa
1.00E-08	6.94E-11	0.48	4.79E-10	-6.4	-32.4
5.00E-08	3.47E-10	2.39	2.39E-09	7.6	-18.4
2.50E-07	1.74E-09	11.97	1.20E-08	21.6	-4.5
1.25E-06	8.68E-09	59.85	5.99E-08	35.5	9.5
6.25E-06	4.34E-08	299.26	2.99E-07	49.5	23.5
3.13E-05	2.17E-07	1496.32	1.50E-06	63.5	37.5
1.56E-04	1.09E-06	7481.61	7.48E-06	77.5	51.5
7.81E-04	5.43E-06	3.74E+04	3.74E-05	91.5	65.4
0.0039	2.71E-05	1.87E+05	1.87E-04	105.4	79.4
0.0195	1.36E-04	9.35E+05	9.35E-04	119.4	93.4
0.0977	6.78E-04	4.68E+06	0.0047	133.4	107.4
0.4883	0.0034	2.34E+07	0.0234	147.4	121.4
2.44	0.017	1.17E+08	0.1169	161.4	135.3
12.21	0.0848	5.85E+08	0.5845	175.3	149.3
61.04	0.42	2.92E+09	2.92	189.3	163.3
305.18	2.12	1.46E+10	14.61	203.3	177.3
1525.88	10.60	7.31E+10	73.06	217.3	191.3
7.63E+03	52.98	3.65E+11	365.31	231.3	205.2
3.81E+04	264.91	1.83E+12	1826.57	245.2	219.2
1.91E+05	1324.56	9.13E+12	9132.83	259.2	233.2
9.54E+05	6622.79	4.57E+13	4.57E+04	273.2	247.2
4.77E+06	3.31E+04	2.28E+14	2.28E+05	287.2	261.2
2.38E+07	1.66E+05	1.14E+15	1.14E+06	301.2	275.1
1.19E+08	8.28E+05	5.71E+15	5.71E+06	315.1	289.1

TABLE D- 20.
SPL, INTENSITY (AIR),

PRESSURE			SPL		INTENSITY IN AIR = $p^2/\rho c$, where ρc = 416 Pa(s/m)			INTENSITY LEVEL	
					Pa(m/s) =N/(m s) =J/(s m^2)			AIR	WATER
			dB re	dB re				dB re	dB re
μPa	psi	psf	1 μPa	20 μPa	= W/m^2	erg/s-m^2	(psi)(in/s)	1 W/m^2	1 W/m^2
1	1.45E-10	2.09E-08	0	-26	2.403E-15	2.403E-08	4.216E-13	-146.2	-181.7
100000	1.45E-05	0.00209	100	74.0	2.403E-05	240.3	1.37E-07	-46.2	-81.7
6.90E+09	1.00E+00	144.0	196.8	170.8	1.143E+05	1.143E+12	651.4575	50.6	15.1
4.79E+07	6.94E-03	1.	153.6	127.6	5.5116	5.512E+07	0.0314	7.4	-28.1
4.79E-01	6.94E-11	1.0E-08	-6.4	-32.4	5.512E-16	5.512E-09	3.142E-18	-152.6	-188.1
2.39E+00	3.47E-10	5.0E-08	7.6	-18.4	1.378E-14	1.378E-07	7.854E-17	-138.6	-174.1
1.20E+01	1.74E-09	2.5E-07	21.6	-4.5	3.445E-13	3.445E-06	1.964E-15	-124.6	-160.1
5.99E+01	8.68E-09	1.25E-06	35.5	9.5	8.612E-12	8.612E-05	4.909E-14	-110.6	-146.1
2.99E+02	4.34E-08	6.25E-06	49.5	23.5	2.153E-10	0.0022	1.227E-12	-96.7	-132.2
1.50E+03	2.17E-07	3.125E-05	63.5	37.5	5.382E-09	0.0538	3.068E-11	-82.7	-118.2
7.48E+03	1.09E-06	0.0	77.5	51.5	1.346E-07	1.3456	7.67E-10	-68.7	-104.2
3.74E+04	5.43E-06	0.0	91.5	65.4	3.364E-06	33.6403	1.917E-08	-54.7	-90.2
1.87E+05	2.71E-05	0.0	105.4	79.4	8.41E-05	841.0073	4.794E-07	-40.8	-76.3
9.35E+05	1.36E-04	0.0	119.4	93.4	0.0021	2.103E+04	1.198E-05	-26.8	-62.3
4.68E+06	6.78E-04	0.1	133.4	107.4	0.0526	5.256E+05	2.996E-04	-12.8	-48.3
2.34E+07	3.39E-03	0.5	147.4	121.4	1.3141	1.314E+07	0.0075	1.2	-34.3
1.17E+08	1.70E-02	2.4	161.4	135.3	32.8518	3.285E+08	0.1873	15.2	-20.3
5.85E+08	8.48E-02	12.2	175.3	149.3	821.2962	8.213E+09	4.6814	29.1	-6.4
2.92E+09	4.24E-01	61.0	189.3	163.3	2.053E+04	2.053E+11	117.0347	43.1	7.6
1.46E+10	2.12E+00	305.2	203.3	177.3	5.133E+05	5.133E+12	2925.8678	57.1	21.6
7.31E+10	1.06E+01	1525.9	217.3	191.3	1.283E+07	1.283E+14	7.315E+04	71.1	35.6
3.65E+11	5.30E+01	7629.3	231.3	205.2	3.208E+08	3.208E+15	1.829E+06	85.1	49.6
1.83E+12	2.65E+02	38146.4	245.2	219.2	8.02E+09	8.02E+16	4.572E+07	99.0	63.5
9.13E+12	1.32E+03	190732.0	259.2	233.2	2.005E+11	2.005E+18	1.143E+09	113.0	77.5
4.57E+13	6.62E+03	9.54E+05	273.2	247.2	5.013E+12	5.013E+19	2.857E+10	127.0	91.5
2.28E+14	3.31E+04	4.77E+06	287.2	261.2	1.253E+14	1.253E+21	7.143E+11	141.0	105.5

TABLE D- 21.
SPL, INTENSITY (WATER)

PRESSURE			SPL		INTENSITY IN WATER = $p^2/\rho c$ where ρc = 1.5 10^6 Pa(s/m)			INTENSITY LEVEL	
			dB re	dB re	Pa(m/s) =J/(s m^2)		μbar–cm/s	IN WATER dB re	IN AIR dB re
μPa	psi	psf	1 μPa	20 μPa	= W/m^2	(psi)(in/s)	= dyn/(cm-s)	1 W/m^2	1 W/m^2
1	1.45E-10	2.09E-08	0	-26	6.7E-19	1.175E-16	6.7E-22	-181.7	-146.2
100000	1.45E-05	0.00209	100	74.0	6.7E-09	3.819E-11	6.7E-06	-81.7	-46.2
6.90E+09	1.00E+00	144.0	196.8	170.8	31.8663	0.1816	3.19E+04	15.0	50.5
4.79E+07	6.94E-03	1.	153.6	127.6	0.0015	8.76E-06	1.5367	-28.1	7.4
5.0	7.25E-10	1.04E-07	14.0	-12.0	1.68E-17	9.55E-20	1.68E-14	-167.8	-132.3
25.0	3.63E-09	5.22E-07	28.0	1.9	4.19E-16	2.39E-18	4.19E-13	-153.8	-118.3
125.0	1.81E-08	2.61E-06	41.9	15.9	1.05E-14	5.97E-17	1.05E-11	-139.8	-104.3
625.0	9.06E-08	1.31E-05	55.9	29.9	2.62E-13	1.49E-15	2.62E-10	-125.8	-90.3
3125.0	4.53E-07	6.53E-05	69.9	43.9	6.54E-12	3.73E-14	0.000	-111.8	-76.3
1.56E+04	2.27E-06	3.26E-04	83.9	57.9	1.64E-10	9.32E-13	0.000	-97.9	-62.4
7.81E+04	1.13E-05	0.0016	97.9	71.8	4.09E-09	2.33E-11	0.000	-83.9	-48.4
3.91E+05	5.66E-05	0.0082	111.8	85.8	1.02E-07	5.83E-10	0.000	-69.9	-34.4
1.95E+06	2.83E-04	0.0408	125.8	99.8	2.56E-06	1.46E-08	0.003	-55.9	-20.4
9.77E+06	0.0014	0.2039	139.8	113.8	6.39E-05	3.64E-07	0.0639	-41.9	-6.4
4.88E+07	0.0071	1.0	153.8	127.8	0.0016	9.11E-06	1.5974	-28.0	7.5
2.44E+08	0.0354	5.1	167.8	141.7	0.0399	2.28E-04	39.9351	-14.0	21.5
1.22E+09	0.177	25.5	181.7	155.7	0.9984	0.0057	998.3778	0.0	35.5
6.10E+09	0.885	127.4	195.7	169.7	24.9594	0.1423	2.50E+04	14.0	49.5
3.05E+10	4.4	637.2	209.7	183.7	623.9861	3.5567	6.24E+05	28.0	63.5
1.53E+11	22.1	3186.0	223.7	197.6	1.56E+04	88.918	1.56E+07	41.9	77.4
7.63E+11	110.6	1.59E+04	237.6	211.6	3.90E+05	2222.9506	3.9E+08	55.9	91.4
3.81E+12	553.1	7.97E+04	251.6	225.6	9.75E+06	5.56E+04	9.75E+09	69.9	105.4
1.91E+13	2.77E+03	3.98E+05	265.6	239.6	2.44E+08	1.39E+06	2.44E+11	83.9	119.4
9.54E+13	1.38E+04	1.99E+06	279.6	253.6	6.09E+09	3.47E+07	6.09E+12	97.8	133.3
4.77E+14	6.91E+04	9.96E+06	293.6	267.5	1.52E+11	8.68E+08	1.52E+14	111.8	147.3

TABLE D-22.

INTENSITY IN AIR VS WATER

PLANE-WAVE PRESSURE IN AIR TO GET CORRESPONDING INTENSITY IN AIR					INTENSITY Pa(m/s)	PLANE-WAVE PRESSURE IN WATER TO GET CORRESPONDING INTENSITY IN WATER				
			dB re	dB re	=J/(s m^2)				dB re	dB re
μPa	psi	psf	1 μPa	20 μPa	= W/m^2	μPa	psi	psf	1 μPa	20 μPa
1	1.45E-10	2.09E-08	0	-26	**2.40E-15**	59.9	8.68E-09	1.25E-06	35.5	9.5
3	4.59E-10	0.0	10	-16	**2.40E-14**	189.4	2.75E-08	3.95E-06	45.5	19.5
10	1.45E-09	0.0	20	-6	**2.40E-13**	598.9	8.68E-08	1.25E-05	55.5	29.5
32	4.59E-09	0.0	30	4	**2.40E-12**	1893.8	2.75E-07	3.95E-05	65.5	39.5
100	1.45E-08	2.09E-06	40	14	**2.40E-11**	5988.8	8.68E-07	1.25E-04	75.5	49.5
316	4.59E-08	6.60E-06	50	24	**2.40E-10**	1.89E+04	2.75E-06	3.95E-04	85.5	59.5
1000	1.45E-07	2.09E-05	60	34	**2.40E-09**	5.99E+04	8.68E-06	0.0013	95.5	69.5
3162	4.59E-07	6.60E-05	70	44	**2.40E-08**	1.89E+05	2.75E-05	0.004	105.5	79.5
1.00E+04	1.45E-06	2.09E-04	80	54	**2.40E-07**	5.99E+05	8.68E-05	0.0125	115.5	89.5
3.16E+04	4.59E-06	6.60E-04	90	64	**2.40E-06**	1.89E+06	2.75E-04	0.0395	125.5	99.5
1.00E+05	1.45E-05	0.0021	100	74	**2.40E-05**	5.99E+06	8.68E-04	0.125	135.5	109.5
3.16E+05	4.59E-05	0.0066	110	84	**2.40E-04**	1.89E+07	0.0027	0.4	145.5	119.5
1.00E+06	1.45E-04	0.0209	120	94	**0.0024**	5.99E+07	0.0087	1.3	155.5	129.5
3.16E+06	4.59E-04	0.066	130	104	**0.024**	1.89E+08	0.0275	4.0	165.5	139.5
1.00E+07	0.0015	0.2088	140	114	**0.2403**	5.99E+08	0.0868	12.5	175.5	149.5
3.16E+07	0.0046	0.6603	150	124	**2.403**	1.89E+09	0.2746	39.5	185.5	159.5
1.00E+08	0.0	2.088	160	134	**2.40E+01**	5.99E+09	0.9	125.0	195.5	169.5
3.16E+08	0.0	6.6	170	144	**2.40E+02**	1.89E+10	2.7	395.4	205.5	179.5
1.00E+09	0.1	20.9	180	154	**2.40E+03**	5.99E+10	8.7	1250.5	215.5	189.5
3.16E+09	0.5	66.0	190	164	**2.40E+04**	1.89E+11	27.5	3954.3	225.5	199.5
1.00E+10	1.5	208.8	200	174	**2.40E+05**	5.99E+11	86.8	12504.6	235.5	209.5
3.16E+10	4.6	660.3	210	184	**2.40E+06**	1.89E+12	274.6	39543.0	245.5	219.5
1.00E+11	14.5	2088.0	220	194	**2.40E+07**	5.99E+12	868.4	125046.1	255.5	229.5
1.00E+12	145.0	20880.0	240	214	**2.40E+09**	5.99E+13	8683.8	1.25E+06	275.5	249.5
3.16E+12	458.5	66028.4	250	224	**2.40E+10**	1.89E+14	27460.4	3.95E+06	285.5	259.5
3.16E+13	4.59E+03	6.60E+05	270	244	**2.40E+12**	1.89E+15	2.75E+05	3.95E+07	305.5	279.5
3.16E+14	4.59E+04	6.60E+06	290	264	**2.40E+14**	1.89E+16	2.75E+06	3.95E+08	325.5	299.5